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VOLUME XXXIV NUMBER 3

THE PHYSICAL REVIEW

A JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS

CONDUCTED
WITH THE CO-OPERATION OF THE

AMERICAN PHYSICAL SOCIETY

BY

EDWARD L. NICHOLS,
ERNEST MERRITT, and FREDERICK BEDELL.

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MARCH, 1912

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THE PHYSICAL REVIEW
LANCASTER, PA., AND ITHACA, N. Y.
BERLIN: MAYER AND MÜLLER

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In the United States

Annual Subscription $6.00 Single Copies, $ .60

Outside the United States

Annual Subscription $6.50 Single Copies, $ .65

Two volumes of The Physical Review are published annually, these volumes beginning in January and July, respectively, and containing six numbers each. Subscriptions should be sent to the publishers, The Physical Review, *41 North Queen Street, Lancaster, Pa.*, or *Ithaca, N. Y.*; or to Messrs. Mayer and Mueller, *Berlin*. In order that subscriptions may terminate with the December issue, subscriptions for less than one year, terminating in December, will be taken at the yearly rate. Previous to Volume V (July–December, 1897) The Physical Review was published in annual volumes, each containing six bi-monthly numbers, beginning with the July-August number, 1893.

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Entered at the post-office, at Lancaster, Pa., as second class matter.

Volume XXXIV. *March, 1912.* *Number 3*

THE

PHYSICAL REVIEW.

THE SELECTIVE TRANSMISSION AND THE DISPERSION OF THE LIQUID CHLORIDES.

By H. H. Marvin.

Introductory.

THE Sellmeier or Ketteler-Helmholtz dispersion formula, namely,

$$n^2 = K + \frac{a_1}{\lambda^2 - \lambda_1^2} + \frac{a_2}{\lambda^2 - \lambda_2^2} + \cdots,$$

represents satisfactorily the observed values of the refractive index for each of many substances over a wide range of wave-length. It has been used by Langley, Rubens, Paschen and others to represent the results of their observations on rock salt, sylvite, fluorite, quartz and other substances.

The Sellmeier formula is nevertheless open to objection. The value derived from the formula for the dielectric constant of every substance yet tried is considerably smaller than the observed value. Moreover, the wave-length assigned to the infra-red absorption band differs from the observed value, in every instance, by an amount too great to be included within the limits of experimental error.

Maclaurin[1] has recently derived the dispersion formula

$$\frac{n^2 - 1}{n^2 + a} = \frac{K - 1}{K + a} + \frac{c_1}{\lambda^2 - \lambda_1^2} + \frac{c_2}{\lambda^2 - \lambda_2^2} + \cdots,$$

and has shown it to be more satisfactory than that of Sellmeier. He found the formula capable of representing satisfactorily the observed values of the refractive indices of rock salt and fluorite, the constants K and λ_2 being in good agreement with the observed values of the dielectric constant and of the wave-length of the infra-red absorption band,

[1] Maclaurin, Proc. Roy. Soc., 81, *A*, 367, 1908.

respectively. The Maclaurin formula therefore appears to be in better agreement with the results of experiment than that of Sellmeier, in the case of solids.

This conclusion concerning the validity of the dispersion formulæ is of theoretical importance. To make this clear, it may be well to sketch the processes by which the formulæ may be derived.

Let f be the displacement in an ether which resists rotations only. If, for convenience, we take the density of this ether to be unity, the impressed torque F necessary to produce a rotation f is $F = c^2 f$. Here c^2 is a coefficient of elasticity and c is numerically the velocity of a wave in the ether. If there be matter present, the vibrators, whether molecules or systems of electrons, will be polarized so as to produce an additional rotation f'. The total rotation produced by the torque F is thus $f + f'$. The quantity f' will, on the hypothesis of small displacements, be proportional to f, so that we may write

$$f' = (n^2 - 1)f,$$

where n is a constant. We may write for the impressed torque, therefore,

$$F = c^2 f = \frac{c^2}{n^2}(f + f').$$

Here c^2/n^2 is a coefficient of elasticity and c/n is the velocity of a wave in the medium. The constant n is thus the refractive index of the medium with respect to the ether. We must make some assumption at this point concerning the torque F' about the vibrator, in the interior of the medium, which is effective in polarizing the vibrator.

If we assume that this effective torque F' is equal to the torque F impressed on the medium, we may write for the impressed torque

$$F = F' = \frac{c^2}{n^2}(f + f').$$

We thus have

$$n^2 = 1 + \frac{c^2 f'}{F'}. \tag{1}$$

If, however, we assume that the effective torque F' is the sum of the impressed torque F and a contribution due to the polarized vibrators adjacent to that upon which we have fixed our attention, quite a different result is obtained. In estimating the contribution due to the polarized vibrators it is convenient, as in the theory of attractions, to consider separately the influence of the vibrators within an elementary sphere about the point, and that of the external field beyond this. Just

what the contribution of adjacent molecules is depends on the configuration about each vibrator and the character of the forces acting between vibrators; but in any case it is proportional to f' and is compensated locally by reactions on other vibrators. Hence the effective torque about the vibrator is

$$F' = F + mf',$$

where m is a constant. The impressed torque is then

$$F = F' - mf' = \frac{c^2}{n^2}(f + f').$$

We have thus

$$\frac{n^2 - 1}{n^2 + a} = \frac{mf'}{F'}, \tag{2}$$

where

$$a = \frac{c^2}{m} - 1.$$

The relation between the polarization f' and the torque F' which produces it is to be found from the equations of forced vibrations of the molecules. If $p/2\pi$ be the frequency and λ the wave-length of the impinging wave, we are led to the expression[1]

$$\frac{f'}{F} = \frac{A_1}{p^2 - p_1^2} + \frac{A_2}{p^2 - p_2^2} + \cdots = \frac{B_1\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{B_2\lambda^2}{\lambda^2 - \lambda_2^2} + \cdots,$$

where $p_1/2\pi$, etc., are the frequencies of the free vibrations of the vibrators.

If we substitute this expression for f'/F' in equation (1) and introduce the condition that for infinitely long waves $n^2 = K$, where K is the dielectric constant, we are led to the Sellmeier dispersion formula. If we proceed in the same manner with equation (2), we are led to the Maclaurin formula.

The assumption concerning the torque F' effective in producing the polarization of the vibrators is the crucial point in the preceding discussion. Should the Sellmeier formula prove capable of representing the results of experiment, the assumption that F' is equal, approximately at least, to the impressed torque would be justified. If, on the other hand, the Maclaurin formula is found to be more satisfactory than that of Sellmeier, we must conclude that the effective torque and the impressed torque are quite different in value.

The value of the constant a in the Maclaurin formula evidently depends on the influence of the vibrators in the immediate neighborhood

[1] Cf. Larmor, Phil. Trans., 190, *A*, 238, 1897.

of the point where the disturbance is considered. The value of this constant cannot be determined from theory. In the case of a liquid or a gas Larmor[1] has given reason for the belief that the value of a is 2.

Object of the Experiments.

The comparison of the two dispersion formulæ is manifestly incomplete, if it is restricted to the case of solids. Such a comparison for the case of gases would be of little value, since the dispersion of gases is small and the regions of anomalous dispersion are very narrow. The comparison of the formulæ for the case of liquids, however, is practicable.

The results of previous experiments on the refractive indices of liquids are of little value for this comparison, since the range of wave-lengths is too small. The experiments to be described presently were undertaken, therefore, with three objects in view, namely: (1) To compare the merits of the Sellmeier and the Maclaurin dispersion formulæ for the case of liquids; (2) to discover, if possible, the appropriate value or values of the constant a in the Maclaurin formula, for the case of liquids; (3) to investigate the relation between the wave-length of the infra-red absorption band and the constitution of the liquid.

Character of the Experiments.

The substances chosen for experimentation constitute a group of chlorides which are liquid at ordinary temperatures. The chlorides were chosen because as a class they are transparent over a wide range of wave-lengths. The transmissivity of each liquid (the percentage of the incident energy transmitted) was observed over a range of wave-lengths from 1.5μ to 16μ. The refractive indices of those chlorides best suited to the purpose were then observed over a range of wave-lengths extending from the sodium line as far into the infra-red as energy limitations permitted.

Apparatus Employed in Observing Transmissivity.

The arrangement of the apparatus employed in observing the transmissivity of the liquids is shown diagrammatically in Fig. 1. A pencil of radiant energy from the Nernst glower N, focused by the concave mirror C, upon the slit S_3 of the mirror spectrometer, is reflected as a parallel beam by the mirror M_3 toward the rock salt prism P. The beam, after being refracted by the prism, is reflected by the Wadsworth mirror W toward the mirror M_4, which focuses the energy in a spectrum in the plane of the slit S_4. Any desired element of this spectrum may be

[1] Larmor, Phil. Trans., 190, *A*, 233, 1897. What is here denoted by a is Larmor's $4\pi/\lambda - 1$.

thrown upon the slit by rotating into the proper position the prism table upon which P and W are mounted. The energy passing through S_4 is

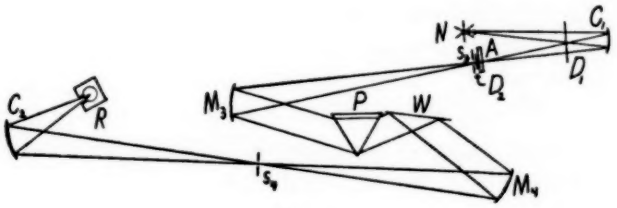

Fig. 1.

focused by the concave mirror C_2 upon the vane of the Nichols radiometer R.

Current for the Nernst glower was supplied by a storage battery. The radiation from the glower was sufficiently constant to permit accurate repetition of observations. The wooden shutter D_1 was used when making observations in the region from 1.5μ to 4.75μ while the shutter D_2 carried glass and fluorite screens which were used in the regions from 4.75μ to 10.75μ and 10.75μ to 16μ respectively. With the glass and the fluorite screens the energy of short wave-length affects by the same amount the zero reading of the radiometer and the reading upon deflection, and the effect of the stray energy as a source of error is thus eliminated.

The spectrometer was by Schmidt & Haensch. The divided circle could be read to 10″ of arc. The instrument was adjusted by a method similar to that described by Langley[1] so that the prism P stood always in the position of minimum deviation for that wave-length which fell upon the slit S_4. The rock salt prism was cut and polished by Brashear. The mean of several determinations of the refracting angle was 59° 59′ 4″.

The vanes of the Nichols radiometer were 1 mm. broad, 5 mm. high, and were mounted about 5 mm. apart. The rock salt window was 3 mm. thick. Deflections were read on a scale placed 110 cm. from the radiometer, and the position of the index on the scale could be read to 0.2 mm. The instrument was only moderately sensitive. The probable deviation of a single observation at 4μ was about 0.2 per cent., at 16μ about 4 per cent.

The body of the absorption cell A was a glass plate 5.5 cm. square and 7 mm. thick, through the center of which was drilled a hole 2.5 cm. in diameter. A tapered hole, drilled from the edge of the plate to the central hole and fitted with a glass stopper, was used in filling the cell. Rock salt plates were cemented over the ends of the central hole, in

[1] Langley, Ann. Astrophys. Observ. Smithsonian Inst., 1, 65, 1900.

which an oblong plate of rock salt was placed in order to reduce the thickness of the layer of liquid through which the beam of energy must pass. Le Page's glue was used as a cement. The cell was mounted before the slit of the spectrometer upon a carriage capable of horizontal motion on a track.

Method of Observing Transmissivity.

The spectrometer was set to transmit the desired wave-length and the deflection produced by the radiation of the Nernst glower was observed. Then the cell containing the liquid was brought before the spectrometer slit, and the deflection produced by the transmitted energy was observed. The zero position of the index on the scale was read before and after each deflection, in order to eliminate errors due to the drift of the zero. Conditions were so steady that it was rarely necessary to repeat an observation except in the neighborhood of an absorption band.

The ratio of the deflection produced by the transmitted energy to that produced by the total energy represents the transmissivity of the liquid and cell walls. The transmissivity of a rock salt plate, of thickness about equal to that of the cell walls, was determined, and the true transmissivity of the liquid was computed. The corresponding wave-length of the energy transmitted was estimated from the spectrometer setting with the aid of the values given by Rubens,[1] and Rubens and Trowbridge,[2] for the refractive index of rock salt.

Apparatus Employed in Observing Refractive Index.

The Nernst glower and the mirror, shutters and cell holder shown in Fig. 1 were removed, and a second spectrometer, similar to that described above, was set up before the slit S_3. It was so placed (Fig. 2) that S_3

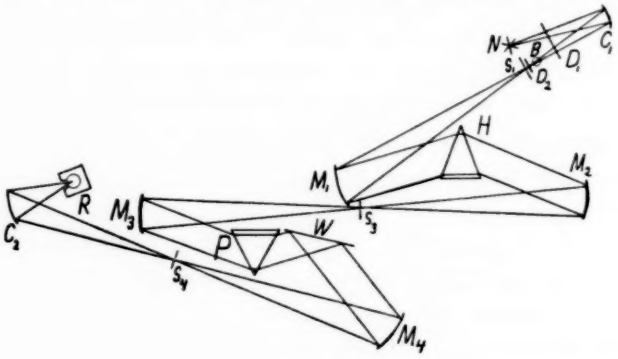

Fig. 2.

[1] Rubens, Wied. Ann., 54, 482, 1895.

[2] Rubens and Trowbridge, Wied. Ann., 61, 224, 1897.

was in the principal focal plane of the mirror M_2, while the line joining the vertices of M_2 and M_3 passed through the center of S_3. The slit S_2 was removed. The fixed arm spectrometer is inconvenient in case the prism is to be changed frequently. This spectrometer was therefore set up as amovable arm instrument. The Nernst glower N, the concave mirror C_1, the shutters D_1 and D_2, and a small Bunsen burner B for use in observations requiring a sodium flame, were mounted on an extension of the movable arm.

The radiant energy from N, which is focused by the mirror C_1 on the slit S_1, is incident after reflection by M_1 as a parallel beam on the hollow prism H which contains the liquid under observation. The prism and the mirror M_2 produce a spectrum in the plane of the slit S_3. Any element of this spectrum can be thrown upon S_3 by rotating the movable arm of the spectrometer to the proper position. The arrangement of the spectrometer bearing the prism P and of the radiometer has been described (Fig. 1).

Two hollow prisms were constructed, the frames being made of brass, the faces of rock salt. The refracting angles were found to be 40° 14′ 20″ and 10° 0′ 20″ respectively. The prism of larger angle was used for observations in the region of short wave-lengths where the dispersion is small, while the prism of smaller angle was used in the region of greater wave-length, where the rapidly diminishing transmissivity of the liquids made imperative a thin absorbing layer.

The top plate of each prism was provided with two holes, for convenience when filling the prism. One hole was closed with a brass stopper when the prism was in use, and a thermometer, by means of which the temperature of the liquid was observed, was inserted through the other hole near the prism base. The brass frame was lined with cover glass, glued in, in order to keep the liquid from contact with the metal.

The construction and mounting of the prisms were such as to secure the maximum amount of transmitted energy. The top and bottom plates of each were triangular, and the rock salt faces were bevelled to fit and were glued together along the refracting edge. The prisms were mounted on brass discs, the levelling screws of each being arranged to fit a point-slot-plane device on the prism table. Each prism was mounted off center, so that the entire height of the refracting edge was illuminated by the incident beam. A thin metal screen cut off that part of the beam which was not incident upon the liquid.

The rock salt plates used as prism faces were about 4 mm. in thickness. The faces were excellently plane, the deviation being not more than 2″. The face of each prism from which the beam emerged was slightly pris-

matic horizontally. A calculation of the resulting error showed that it would be corrected with sufficient accuracy over the entire range of wave-length by the addition of 10″ to the angle of emergence in the case of the 40° prism, or by the addition of 40″ in the case of the 10° prism. These corrections were later changed to 0″ and 20″ respectively upon repolishing the exterior surfaces of the prisms.

Method of Observing Refractive Index.

The method of observing refractive index is based on the fact that, if the slits are very narrow, no energy from the Nernst glower can reach the radiometer until both spectrometers are set to transmit energy of the same wave-length. The wave-length may then be estimated from the setting of the spectrometer which bears the prism P the dispersion of which is known. The refractive index of the liquid contained in the prism H for energy of this wave-length may be computed from the setting of the spectrometer upon which H is mounted.

At the beginning of each set of observations the prism H was placed upon the prism table and fixed in a position suitable for observations on the liquid contained in the prism. The angle of emergence, which was therefore constant during the set of observations, was so chosen that the prism was in the position of minimum deviation for some wave-length in the infra-red. Energy of the desired wave-length was then thrown upon the slit S_3 by rotating the movable spectrometer arm to the proper position. The angle of incidence i and the angle of emergence e for the prism H were computed from the prism angle α and the divided circle readings. The refractive index, n, of the liquid was computed according to the formula

$$n^2 = \frac{1}{\sin^2 \alpha} \{\sin i + \cos \alpha \cdot \sin e\}^2 + \sin^2 e.$$

The estimation of the mean wave-length of the energy focused on the slit S_3 was complicated by the finite width of the slits. Energy from the source could reach the radiometer when the prism P was set in any position in a narrow region which included the position corresponding to the mean wave-length. In case the emission of the glower and the transmissivity of the optical system did not vary with wave-length in this region, the mean wave-length could be estimated from the prism setting corresponding to the maximum radiometer deflection. This condition was, in general, not satisfied. The variation of the energy due to these causes was, however, very nearly proportional to the variation with wave-length of the radiometer deflections when the absorption cell A

(Fig. 1) was before the slit. The radiometer deflections being corrected in accordance with this principle, the mean wave-length could be calculated from the prism setting corresponding to the maximum (corrected) radiometer deflection.

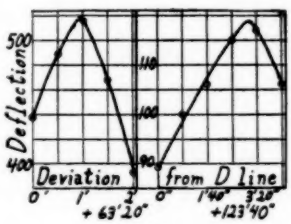

Fig. 3.

Radiometer deflections were therefore observed with the prism P in various positions in the neighborhood of the position corresponding to the maximum radiometer deflection. The corrected deflections were plotted as ordinates with prism settings as abscissæ (Fig. 3), and the wave-length was then estimated with the aid of the values given by Paschen[1] for the refractive index of rock salt.[2]

The observations upon each liquid were reduced to a common temperature, because of the large temperature coefficient of refractive indices of liquids. No correction for the temperature coefficient of refractive index of rock salt was necessary, since only its variation with wave-length (which Liebreich[3] has shown to be very small in the infra-red) can affect the estimation of wave-length by the fixed arm spectrometer. The error resulting from this variation was in every case smaller than the probable experimental error.

Results of Transmissivity Observations.

The liquids available were:

Monochlorides—S_2Cl_2, BrCl, ICl,
Dichlorides—C_2Cl_4,
Trichlorides—PCl_3, $AsCl_3$,
Tetrachlorides—CCl_4, $SiCl_4$, $TiCl_4$, $SnCl_4$,
Pentachlorides—$SbCl_5$.

All were rated C.P. by the makers. The purity of the liquids was not tested, for the following reasons. The transmissivity observations agreed sufficiently well with the observations of earlier observers to make reasonable the assumption that no considerable amount of impurity was present. Moreover, because of the additive law of dispersion, the effect of an impurity on the dispersion could be taken into account by including in the dispersion formula terms corresponding to the absorption bands of the impurity.

[1] Paschen, Ann. d. Phys., 26, 120, 1908.

[2] Paschen's values are somewhat more self-consistent than those of Rubens, and Rubens and Trowbridge.

[3] Liebreich, Ber. Deutsch. Phys. Gesell., 13, 1, 1911.

The results of the observations on the transmissivity of the above liquids are shown by the curves in Figs. 4 to 12. The ordinates represent

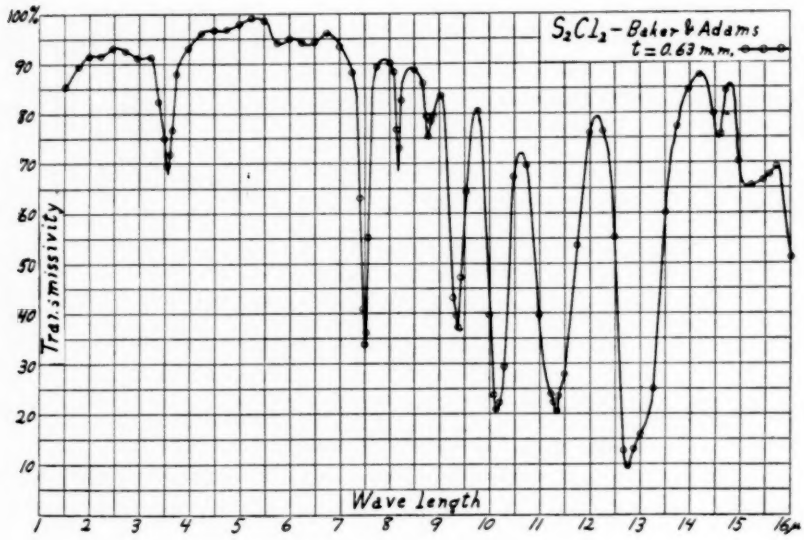

Fig. 4.

transmissivity, the abscissæ wave-length in μ. The name of the manufacturer and the thickness t of the absorbing layer of the liquid are given

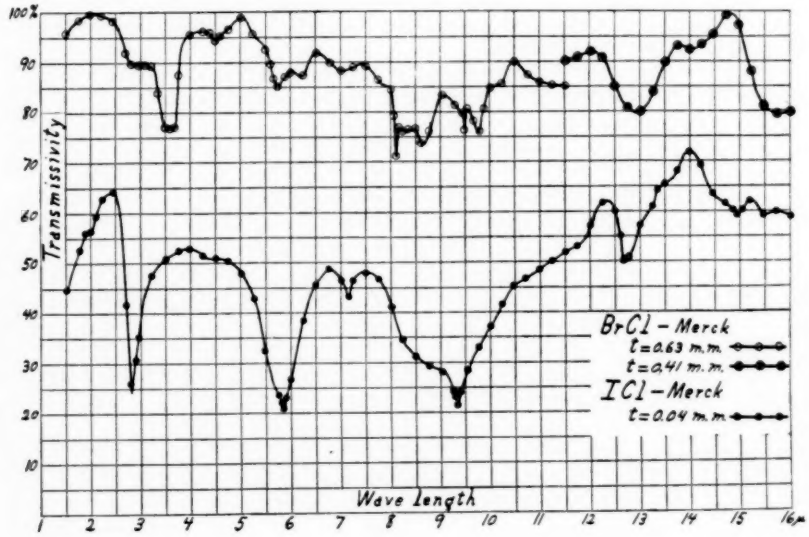

Fig. 5.

with each curve. The wave-lengths of the absorption bands, estimated according to the values of the refractive index of rock salt given by

Rubens, and Rubens and Trowbridge, and by Paschen, are shown in Table I. They are designated by (*R*) and (*P*) respectively.

TABLE I.

Liquid.	Wave-length of Absorption Bands in μ.
S_2Cl_2	(*R*) 3.56, 7.50, 8.17, 8.77, 9.37, 10.15, 11.33, 12.71, 14.55, 15.20
	(*P*) 3.61, 7.49, 8.12, 8.73, 9.34, 10.13, 11.36, 12.72, 14.52, 15.17
BrCl	(*R*) 3.58, 8.13, 9.48, 9.76, 12.9
	(*P*) 3.63, 8.08, 9.46, 9.74, 12.9
ICl	(*R*) 2.83, 5.85, 7.13, 9.32, 12.7
	(*P*) 2.90, 5.92, 7.13, 9.30, 12.7
PCl_3	(*R*) 3.50, 3.65, 7.71, 8.29, 10.13, 10.26, 11.48, 13.15, 14.85
	(*P*) 3.55, 3.70, 7.69, 8.24, 10.11, 10.24, 11.51, 13.14, 14.82
$AsCl_3$	(*R*) 2.74, 3.15, 6.17, 13.0 – 13.7
	(*P*) 2.82, 3.21, 6.23, 13.0 – 13.7
CCl_4	(*R*) 4.25, 6.41, 8.04, 8.29, 9.15, 9.96, 10.23, 12.72, 13.10, 14.92
	(*P*) 4.31, 6.47, 7.99, 8.24, 9.13, 9.94, 10.21, 12.73, 13.09, 14.89
$SiCl_4$	(*R*) 3.21, 4.34, 5.47, 6.53, 8.25, 8.95, 9.76, 10.75, 13.23, 15.10
	(*P*) 3.27, 4.40, 5.53, 6.60, 8.20, 8.92, 9.74, 10.75, 13.21, 15.13
$TiCl_4$	(*R*) 3.13, 6.18, 10.19, 11.41, 12.15
	(*P*) 3.19, 6.24, 10.17, 11.43, 12.19
$SnCl_4$	(*R*) 3.08, 3.45, 6.29, 8.24, 11.25, 12.26, 13.06, 15.12
	(*P*) 3.15, 3.50, 6.34, 8.19, 11.25, 12.30, 13.05, 15.09
$SbCl_5$	(*R*) 2.85, 4.27, 6.28, 9.28, 12.49, 13.3 – 14.0, 14.8 – 15.0, 15.75
	(*P*) 2.92, 4.34, 6.33, 9.26, 12.52, 13.3 – 14.0, 14.8 – 15.0, 15.75
LePage's Glue	(*R*) 2.9 – 3.05, 5.97 – 6.03
	(*P*) 2.98 – 3.12, 6.04 – 6.10

Each liquid has a strongly characteristic transmission spectrum. However, the spectra of those liquids whose bases are related show similarities. Each band in the spectrum of $SbCl_5$, with the exception of that at 9.28μ, appears to correspond to a band of slightly shorter wave-length in the spectrum of $AsCl_3$. A triple group appears in the spectrum of $SiCl_4$ between 8μ and 10μ, while in the spectrum of $TiCl_4$ a similar group appears between 10μ and 12.5μ. It seems possible, therefore, that the absorption bands of the liquid chlorides in the region of wave-lengths under consideration are characteristic of the bases. The similarity of the triple group in the $SiCl_4$ spectrum and the group in the spectrum of

quartz; of the group in the $TiCl_4$ spectrum and the band in the reflection spectrum of TiO_2; and the frequent occurrence of several of the bands

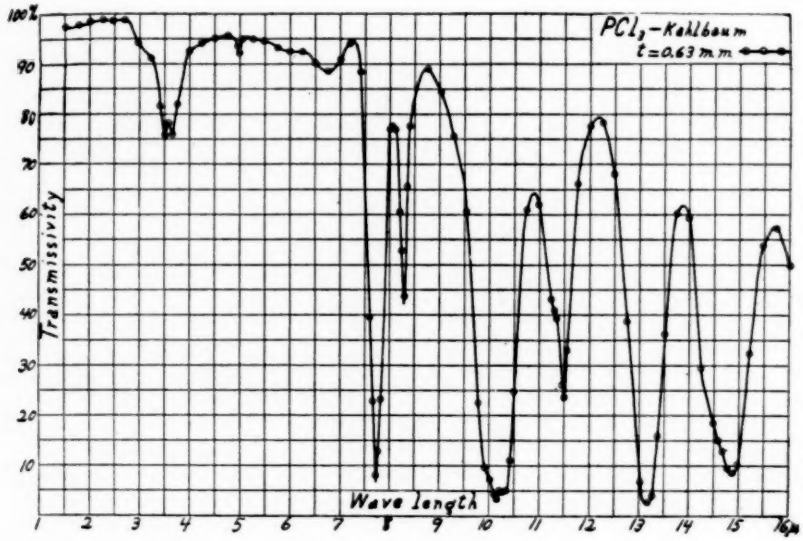

Fig. 6.

of the S_2Cl_2 spectrum in the spectra of other compounds of sulphur, all point toward the same conclusion.

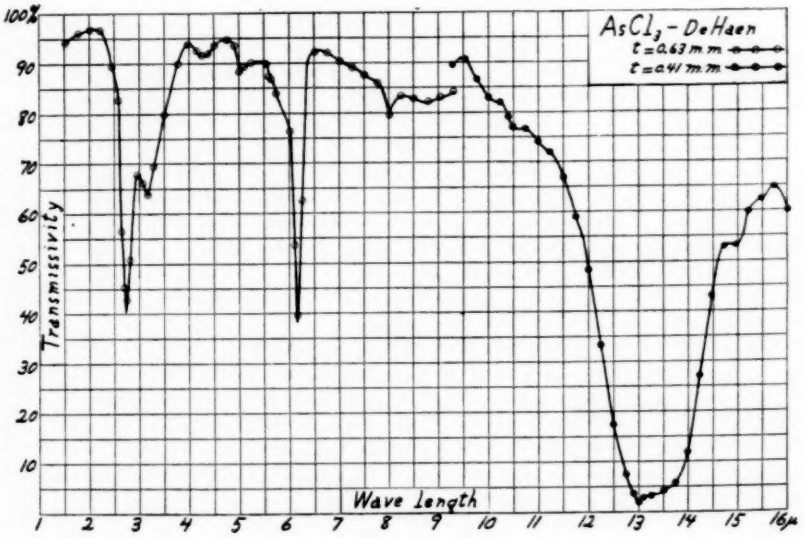

Fig. 7.

The strong absorption band of CCl_4 near 13μ could not be analyzed even with a very thin absorbing layer of the liquid. By the use of BrCl

containing a little CCl_4 as the absorbing medium, the band was found to be complex, the minima being at 12.72μ and 13.11μ.

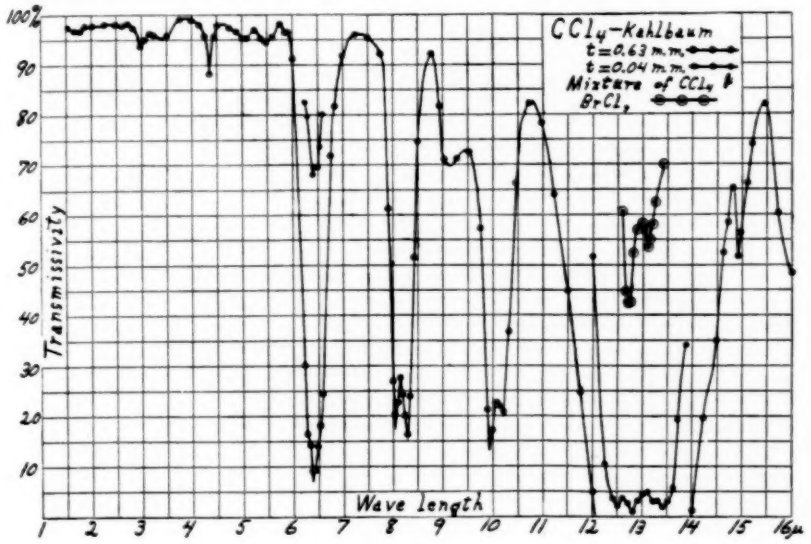

Fig. 8.

The transmissivity of Le Page's glue was observed (Fig. 13) since it was used as a cement. No marked absorption bands were found, other

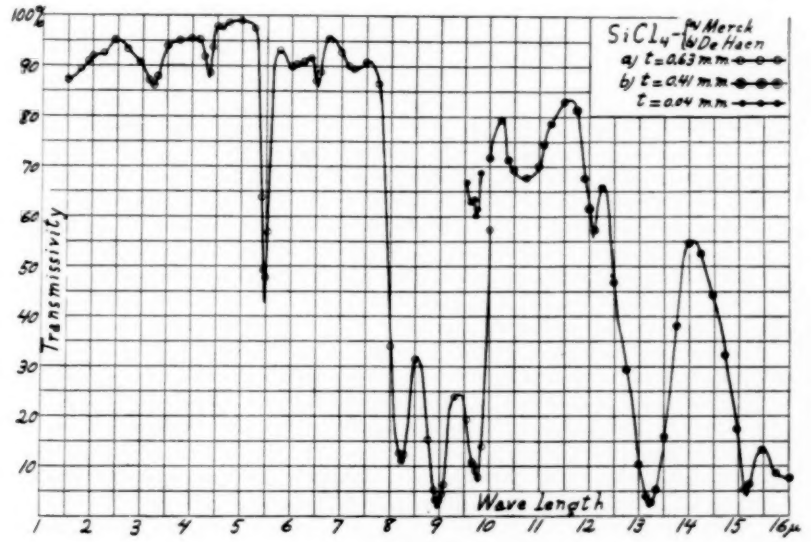

Fig. 9.

than the acetic bands previously observed by Coblentz.

The wave-lengths of the strong absorption bands of S_2Cl_2, C_2Cl_4, PCl_3,

TABLE II.

Liquid.	Observer.	Wave-length of Absorption Bands in μ.
CCl_4....	Coblentz	(*R*) 6.45, 6.57, 8.02, 8.25, 9.0–9.3, 10.1, 12.3–13.6
	Julius	(*R*) 6.41, 8.19, 10.14
C_2Cl_4....	Coblentz	(*R*) 5.6, 7.5, 9.0, 10.2, 11.0, 12.5–13.4, 14.7
S_2Cl_2....	Julius	(*R*) 7.50, 9.33, 10.16
PCl_3.....	Julius	(*R*) 7.71, 10.08
$SiCl_4$....	Julius	(*R*) 5.52, 8.19, 8.93, 9.62

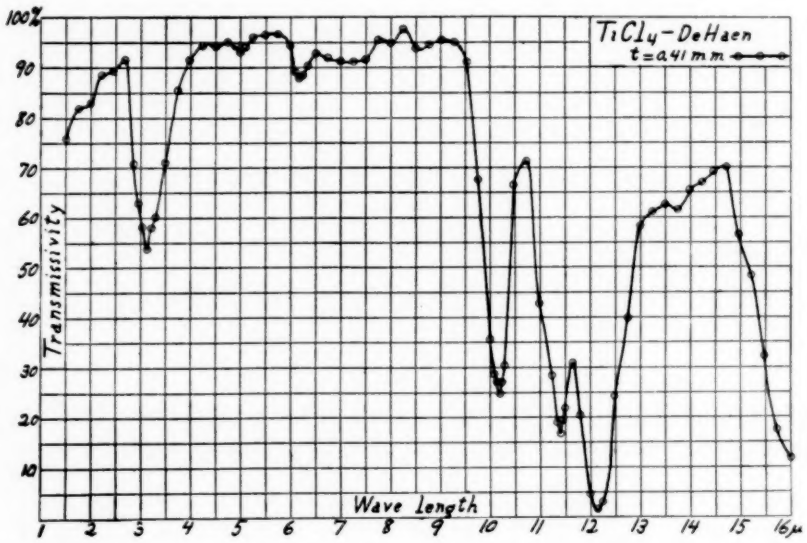

Fig. 10.

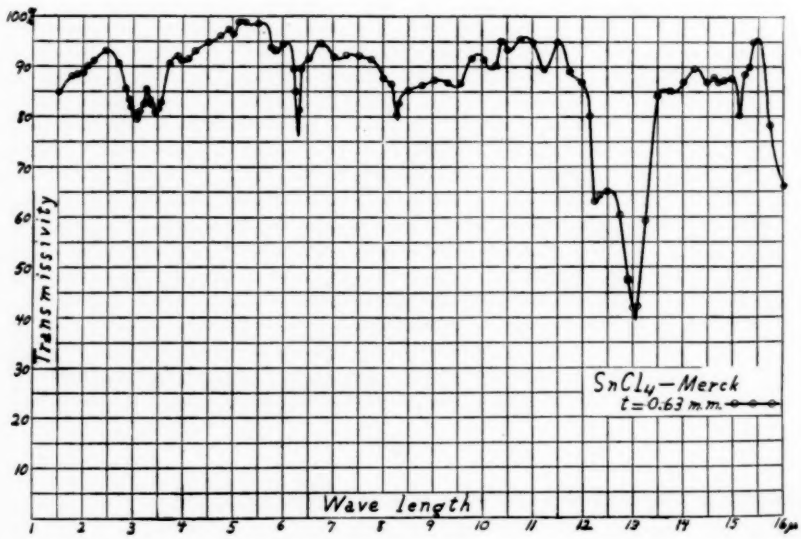

Fig. 11.

CCl_4, and $SiCl_4$, according to Coblentz[1] and Julius,[2] are given for comparison in Table II. The agreement between the various observations

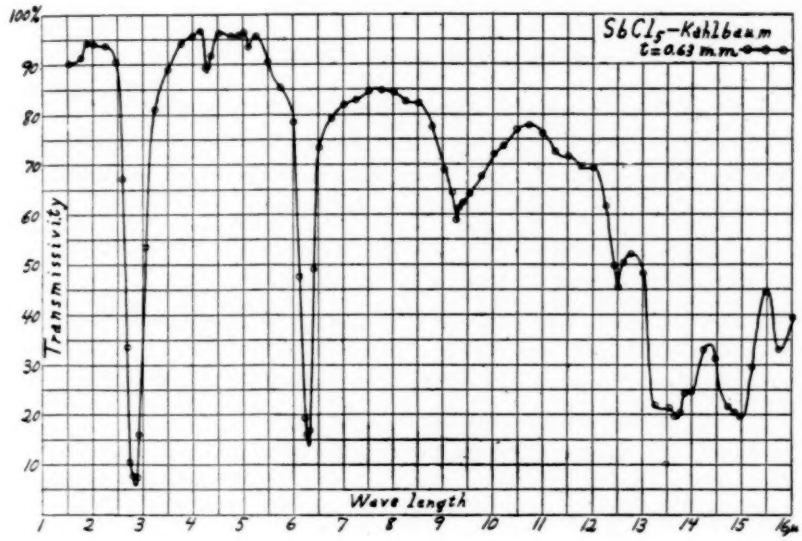

Fig. 12.

of the wave-length of sharp, detached bands, such as those of S_2Cl_2 at 7.50μ, PCl_5 at 7.71μ, CCl_4 at 6.41μ and $SiCl_4$ at 5.47μ is very good. The

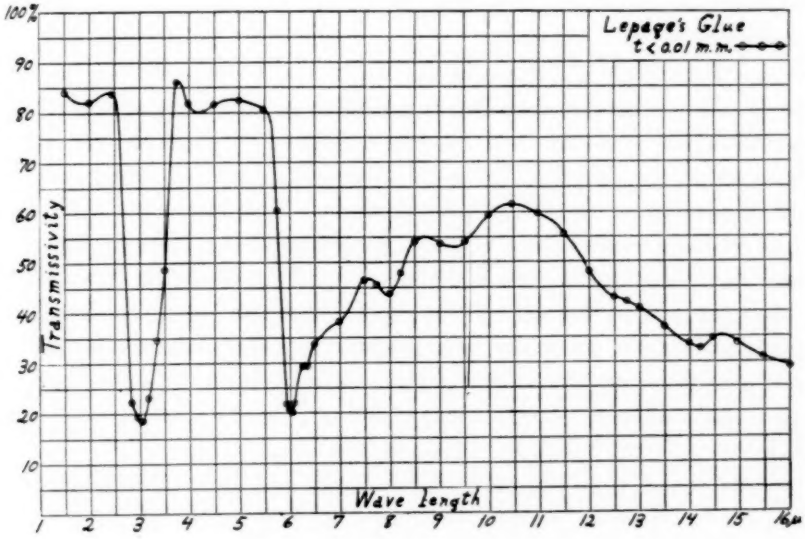

Fig. 13.

[1] Coblentz, Investigations of Infra-red Spectra, Vol. I., 1905.

[2] Julius, Verh. d. kongh. Akad. d. Wetenschaft, Amsterdam, 1, 1, 1892.

small slit width used in the present work has made possible greater resolution of complex bands. This has resulted in the assignment of new values for the wave-lengths of minor bands in several groups.

Results of Dispersion Observations.

The refractive indices of eight liquids were observed. PCl_3, BrCl, and ICl were not used, because of difficulties which need not be discussed in detail. The dispersion of each liquid was found to be large in the neighborhood of the visible spectrum, diminishing to a minimum in the region $2.5-5\mu$ and increasing toward the greater wave-lengths. The minimum value of the dispersion is much smaller than is the case for solids. Anomalous dispersion is shown in the neighborhood of strong absorption bands, the refractive index being abnormally small on the side of the band toward the short wave-lengths and abnormally large on the side toward the great wave-lengths.

S_2Cl_2, C_2Cl_4, $AsCl_3$.—The value of the constants in the dispersion formulæ were not calculated for these liquids. The numerous absorption bands in the spectrum of S_2Cl_2 would render the adjustment of the constants very difficult, while the observations with C_2Cl_4 and $AsCl_3$ were not extended over a sufficient range of wave-lengths to make dispersion formulæ for these substances of much value. The experimental data for these liquids is given in Table III. The temperature to which observations were reduced is represented by T, the wave-length in μ by λ and the refractive index by n.

The values of the constants in the dispersion formulæ for the remaining five liquids were adjusted by a method of approximation. A first approximation was obtained for the dielectric constant K and for the constants of the principal infra-red absorption band on the assumption that dispersion is due to this band alone. The terms for the smaller infra-red bands were then introduced. Finally, the term for the ultra-violet band was introduced and the value of the dielectric constant and of the constants of the ultra-violet and the infra-red bands were adjusted by approximation until the best possible agreement between the computed and the observed values of the refractive index was obtained. In case a reasonably good agreement could not be obtained by assuming a single strong infra-red band, a second band was introduced.

It was found that the Sellmeier formula and that of Maclaurin can be made to represent equally well the observed values of the refractive index, if the choice of constants be unrestricted. In order to decide which is the more satisfactory, the constants of each must be compared with the experimental values of the wave-length of the infra-red absorp-

tion band and of the dielectric constant. Maclaurin found the same to be necessary in the case of rock salt and fluorite. The wave-lengths of the infra-red bands of the liquid chlorides are unknown, but the dielectric constants of nearly all have been determined by Turner,[1] Drude[2] and Schlundt.[3]

TABLE III.

S_2Cl_2.		C_2Cl_4.		$AsCl_3$.	
$T = 22.9°$ C.		$T = 22.8°$ C.		$T = 22.2°$ C.	
λ	n	λ	n	λ	n
0.589	1.67061	0.589	1.50410	0.589	1.59714
1.017	1.64149	1.019	1.49145	0.995	1.57925
1.613	1.63365	1.544	1.48790	1.444	1.57356
2.117	1.63138	2.081	1.48657	1.900	1.57205
2.526	1.63027	2.558	1.48585	2.474	1.57033
3.036	1.62940	3.097	1.48525	2.950	1.56956
3.268	1.62905	3.738	1.48440	3.381	1.56926
3.919	1.62841	4.546	1.48332	3.912	1.56825
4.184	1.62782	4.976	1.48232	4.546	1.56721
4.644	1.62718	5.504	1.48084	5.054	1.56594
5.144	1.62654	6.075	1.47969	5.630	1.56465
5.652	1.62584	6.676	1.47855	6.033	1.56374
6.063	1.62502	6.919	1.47649	6.550	1.56325
6.841	1.62356	7.562	1.47328	7.000	1.56172
7.141	1.62256	8.34	1.4670	7.655	1.56011
7.883	1.62251			8.205	1.55904
7.920	1.62204			8.830	1.55594
7.961	1.62174			9.152	1.55469
8.360	1.62063			9.31	1.5533
8.431	1.61999			9.62	1.5505
8.947	1.61876			9.93	1.5464
9.70	1.6163				
10.61	1.6144				
12.08	1.6094				
12.15	1.6083				
12.19	1.6072				
13.84	1.6004				
14.10	1.5968				
14.49	1.5946				
14.55	1.5932				

Antimony Pentachloride—$SbCl_5$.—A comparative study of the Sellmeier and the Maclaurin formulæ was made, the data for $SbCl_5$ being used because of the simplicity of the dispersion curve for this substance. Formulæ *A*, *B*, and *C* are of the Maclaurin type, set up in precisely the same manner, arbitrary values being chosen for a and K, these values

[1] Turner, Zeitschr. Phys. Chem., 35, 385, 1900.

[2] Drude, Zeitschr. Phys. Chem., 23, 267, 1897.

[3] Schlundt, Journ. Phys. Chem., 5, 503, 1901; 8, 122, 1904.

TABLE IV.

$SbCl_5$.

Formula.	A	B	C	D	E	
c_1	.0039662	.0041975	.0044269	.0042497	a_1	.028066
λ_1^2	.050377	.050428	.050376	.046947	λ_1^2	.05196
c_2	.00010	.00009	.00010	.00009	a_2	.0006
λ_2^2	8.703	8.703	8.703	8.703	λ_2^2	8.703
c_3	.00044	.00044	.00044	.00044	a_3	.0030
λ_3^2	40.069	40.069	40.069	40.069	λ_3^2	40.069
c_4	.12193	.27904	.20698	.21572	a_4	.56242
λ_4^2	191.26	212.96	198.06	202.58	λ_4^2	184.81
c_5	182.15	362.17	664.10	439.79	a_5	952.53
λ_5^2	1748.6	2450.5	3170.6	2670.9	λ_5^2	1506.7
a	2.5	2.0	1.5	2.0		——
K	3.3	3.7	4.4	3.886	K	3.077

TABLE V.

$SbCl_5$.

Reduced to 21.9° C.

Formula.		A		B		C		D		E	
λ	n (Observed).	n (Computed).	$d \times 10^4$.	n (Computed).	$d \times 10^4$.	n (Computed).	$d \times 10^4$.	n (Computed).	$d \times 10^4$.	n (Computed).	$d \times 10^4$.
0.589	1.59255	1.5926	0	1.5926	0	1.5926	0	1.5926	0	1.5926	0
0.988	1.57210	1.5720	—1	1.5720	—1	1.5720	—1	1.5721	0	1.5721	0
1.527	1.56605	1.5661	0	1.5661	0	1.5661	0	1.5661	0	1.5661	0
2.045	1.56415	1.5641	0	1.5641	0	1.5641	0	1.5641	0	1.5641	0
2.453	1.56311	1.5631	0	1.5631	0	1.5631	0	1.5631	0	1.5632	+1
3.316	1.56190	1.5619	0	1.5619	0	1.5619	0	1.5619	0	1.5620	+1
3.615	1.56136	1.5614	0	1.5614	0	1.5615	+1	1.5614	0	1.5615	+1
4.182	1.56059	1.5606	0	1.5606	0	1.5606	0	1.5606	0	1.5606	0
4.598	1.55999	1.5600	0	1.5600	0	1.5600	0	1.5600	0	1.5600	0
5.072	1.55922	1.5592	0	1.5592	0	1.5592	0	1.5592	0	1.5592	0
5.519	1.55839	1.5584	0	1.5584	0	1.5584	0	1.5584	0	1.5584	0
6.076	1.55743	1.5572	—2	1.5572	—2	1.5572	—2	1.5572	—2	1.5572	—2
6.666	1.55678	1.5565	—3	1.5565	—3	1.5565	—3	1.5565	—3	1.5566	—2
7.046	1.55559	1.5556	0	1.5556	0	1.5556	0	1.5556	0	1.5556	0
7.496	1.55440	1.5545	+1	1.5545	+1	1.5545	+1	1.5545	+1	1.5545	+1
7.963	1.55320	1.5534	+2	1.5534	+2	1.5534	+2	1.5534	+2	1.5534	+2
8.466	1.55195	1.5520	0	1.5520	0	1.5520	0	1.5520	0	1.5520	0
8.942	1.55075	1.5506	—2	1.5506	—2	1.5506	—2	1.5506	—2	1.5506	—2
9.355	1.54944	1.5493	—1	1.5493	—1	1.5494	0	1.5494	0	1.5493	—1
9.768	1.54800	1.5480	0	1.5480	0	1.5480	0	1.5480	0	1.5480	0
10.371	1.54573	1.5457	0	1.5457	0	1.5457	0	1.5457	0	1.5457	0
11.083	1.54274	1.5427	0	1.5427	0	1.5427	0	1.5427	0	1.5427	0
11.615	1.53992	1.5400	+1	1.5400	+1	1.5400	+1	1.5399	0	1.5400	+1
12.138	1.53703	1.5368	—2	1.5368	—2	1.5367	—3	1.5368	—2	1.5368	—2

giving the closest possible agreement between the computed and observed values of the refractive index. Formula D is also of the Maclaurin type, the value of a being taken as 2, the value of K being found by approximation. Formula E is of the Sellmeier type, K being found by approximation. The values of the constants in these formulæ are given in Table IV. In Table V. are given the observed values of the refractive index, the values computed from the formulæ, and the differences between the computed and the observed values.

The values of the refractive index computed from these formulæ are in equally good agreement with the observed values. The value of K in formula B, however, is in good agreement with the value 3.78 for the dielectric constant of $SbCl_5$ observed by Schlundt, while the values of K in formulæ A and C are widely different. Likewise, the value of K in formula D is in much better agreement with the dielectric constant than

TABLE VI.

CCl_4.

Reduced to 21.8° C.		Maclaurin Formula.		Sellmeier Formula.	
λ	n (Observed).	n (Computed).	$d \times 10^4$.	n (Computed).	$d \times 10^4$.
0.434[1]	1.47149	1.4715	0	1.4715	0
0.486[1]	1.46588	1.4659	0	1.4659	0
0.589	1.45932	1.4593	0	1.4593	0
0.656[1]	1.45659	1.4566	0	1.4566	0
0.928	1.45151	1.4513	— 2	1.4513	— 2
1.312	1.44859	1.4486	0	1.4486	0
1.756	1.44713	1.4471	0	1.4471	0
2.298	1.44592	1.4460	+ 1	1.4459	0
2.938	1.44476	1.4448	0	1.4448	0
3.542	1.44348	1.4435	0	1.4435	0
4.045	1.44226	1.4423	0	1.4423	0
4.565	1.44080	1.4408	0	1.4408	0
5.074	1.43932	1.4391	— 2	1.4391	— 2
5.659	1.43678	1.4366	— 2	1.4366	— 2
6.153	1.43360	1.4336	0	1.4336	0
6.923	1.43109	1.4310	— 1	1.4310	— 1
7.365	1.42709	1.4271	0	1.4271	0
7.716	1.42295	1.4232	+ 2	1.4232	+ 2
8.576	1.41558	1.4157	+ 1	1.4156	0
8.911	1.40911	1.4099	+ 8	1.4098	+ 7
9.14	1.4028	1.4028	0	1.4028	0
9.59	1.3967	1.3966	— 1	1.3965	— 2
10.59	1.3613	1.3624	+11	1.3623	+10
10.79	1.3498	1.3502	+ 4	1.3502	+ 4
11.18	1.3197	1.3197	0	1.3197	0
11.37	1.2985	1.2985	0	1.2984	— 1
15.07	1.5897	1.5897	0	1.5897	0
15.36	1.5765	1.5765	0	1.5765	0

[1] Observed with the Pulfrich refractometer.

is the value of K in formula E. These comparisons indicate that the Maclaurin formula represents the results of experiment better than does the Sellmeier formula, and that the most probable value of the constant a is nearly, if not exactly 2.

The Tetrachlorides.—The observed values of the refractive index of CCl_4, the values computed from the Maclaurin and the Sellmeier formulæ and the differences between the computed and the observed values are given in Table VI. The values of the constants in the formulæ are

Maclaurin Formula.		Sellmeier Formula.	
$a = 2,$	$K = 2.2086,$		$K = 2.2084,$
$c_1 = 0.0021747,$	$\lambda_1^2 = 0.018861,$	$a_1 = 0.012158,$	$\lambda_1^2 = 0.021348,$
$c_2 = 0.00271,$	$\lambda_2^2 = 42.12,$	$a_2 = 0.0143,$	$\lambda_2^2 = 42.12,$
$c_3 = 0.00431,$	$\lambda_3^2 = 65.94,$	$a_3 = 0.0221,$	$\lambda_3^2 = 65.94,$
$c_4 = 0.00147,$	$\lambda_4^2 = 84.27,$	$a_4 = 0.0079,$	$\lambda_4^2 = 84.27,$
$c_5 = 0.00300,$	$\lambda_5^2 = 100.00,$	$a_5 = 0.0154,$	$\lambda_5^2 = 100.00,$
$c_6 = 2.7388,$	$\lambda_6^2 = 159.72,$	$a_6 = 12.301,$	$\lambda_6^2 = 162.61,$
$c_7 = 0.50168,$	$\lambda_7^2 = 173.15,$	$a_7 = 6.8266,$	$\lambda_7^2 = 173.21.$

The values of K in the two formulæ are in equally good agreement with the mean of the values 2.18 and 2.246 for the dielectric constant observed by Drude and Turner respectively. The value of λ_6, 12.64μ, in the Maclaurin formula is not in as good agreement with the observed wavelength 12.73μ of the infra-red band as is the value 12.75μ in the Sellmeier formula. The agreement is satisfactory, however, in either case. It is to be noted that this absorption band causes an inversion in the spectrum of CCl_4, the value of the refractive index at 15μ being much greater than is its value in the visible.

The observed and the computed values of the refractive index of $SiCl_4$, and the differences between them, are given in Table VII. The values of the constants in the dispersion formulæ are

Maclaurin Formula.		Sellmeier Formula.	
$a = 2,$	$K = 2.3228,$		$K = 2.1824,$
$c_1 = 0.0015563,$	$\lambda_1^2 = 0.079867,$	$a_1 = 0.0082361,$	$\lambda_1^2 = 0.080730,$
$c_2 = 0.00033,$	$\lambda_2^2 = 30.703,$	$a_2 = 0.00175,$	$\lambda_2^2 = 30.703,$
$c_3 = 0.00332,$	$\lambda_3^2 = 68.063,$	$a_3 = 0.0163,$	$\lambda_3^2 = 68.063,$
$c_4 = 0.01660,$	$\lambda_4^2 = 79.210,$	$a_4 = 0.0797,$	$\lambda_4^2 = 79.210,$
$c_5 = 0.00996,$	$\lambda_5^2 = 94.868,$	$a_5 = 0.0562,$	$\lambda_5^2 = 94.868,$
$c_6 = 0.39840,$	$\lambda_6^2 = 175.03,$	$a_6 = 0.84428,$	$\lambda_6^2 = 175.03,$
$c_7 = 0.59760,$	$\lambda_7^2 = 228.80,$	$a_7 = 57.865,$	$\lambda_7^2 = 276.71.$
$c_8 = 8.7132,$	$\lambda_8^2 = 275.45,$		
$c_9 = 56.904,$	$\lambda_9^2 = 2238.2.$		

It was necessary in setting up the Maclaurin formula to take account of the band at 15.13μ and to assume two strong bands of greater wave-

length, in order to obtain a satisfactory agreement between computed and observed values of the refractive index. Similar agreement was obtained with less difficulty in the case of the Sellmeier formula. The value of K in the Maclaurin formula is in better agreement with the dielectric constant, 2.40, observed by Schlundt than is the value of K in the Sellmeier formula. The latter might be increased by assuming a second strong infra-red band, but could not be made greater than 2.25.

TABLE VII.

$SiCl_4$.

Reduced to 22.4° C.		Maclaurin Formula.		Sellmeier Formula.	
λ	n (Observed).	n (Computed).	$d \times 10^4$.	n (Computed).	$d \times 10^4$.
0.589	1.41318	1.4132	0	1.4132	0
1.031	1.40504	1.4050	0	1.4050	0
1.539	1.40275	1.4029	+ 1	1.4029	+ 1
2.030	1.40158	1.4019	+ 3	1.4018	+ 2
2.523	1.40071	1.4009	+ 2	1.4009	+ 2
3.008	1.39985	1.3999	0	1.3999	0
3.366	1.39917	1.3992	0	1.3992	0
3.733	1.39830	1.3983	0	1.3983	0
4.118	1.39719	1.3972	0	1.3972	0
4.579	1.39589	1.3958	— 1	1.3959	0
5.094	1.39391	1.3940	+ 1	1.3939	0
5.286	1.39316	1.3932	0	1.3932	0
5.762	1.39155	1.3916	0	1.3916	0
6.029	1.39019	1.3902	0	1.3902	0
6.395	1.38832	1.3883	0	1.3883	0
6.896	1.38559	1.3854	— 2	1.3854	— 2
7.365	1.38230	1.3820	— 3	1.3820	— 3
7.581	1.38012	1.3802	+ 1	1.3801	0
10.05	1.3635	1.3622	—13	1.3623	—12
10.46	1.3546	1.3538	— 8	1.3535	—11
10.81	1.3455	1.3462	+ 7	1.3458	+ 3
11.30	1.3334	1.3344	+10	1.3340	+ 6
11.57	1.3262	1.3264	+ 2	1.3265	+ 3

No comparison of the formula is possible in the case of $TiCl_4$, since the dielectric constant is unknown. The observed values of the refractive index and the values computed from the Maclaurin formula, together with the differences between them, are given in Table VIII. The constants of the formula are

Maclaurin Formula.

$a = 2$, $K = 2.8114$, $c_4 = 0.05867$, $\lambda_4^2 = 147.62$,
$c_1 = 0.0057848$, $\lambda_1^2 = 0.050458$, $c_5 = 0.77654$, $\lambda_5^2 = 261.41$,
$c_2 = 0.00199$, $\lambda_2^2 = 103.23$, $c_6 = 21.691$, $\lambda_6^2 = 449.52$.
$c_3 = 0.00597$, $\lambda_3^2 = 129.73$.

TABLE VIII.

$TiCl_4$.

Reduced to 20.3° C.		Maclaurin Formula.		Reduced to 20.3° C.		Maclaurin Formula.	
λ	n (Observed).	n (Computed).	$d \times 10^4$.	λ	n (Observed).	n (Computed).	$d \times 10^4$.
0.589	1.60604	1.6060	0	6.534	1.55237	1.5524	0
1.012	1.57665	1.5767	0	7.010	1.55010	1.5503	+2
1.524	1.56920	1.5692	0	7.584	1.54759	1.5474	—2
2.064	1.56611	1.5661	0	8.071	1.54459	1.5446	0
2.500	1.56469	1.5647	0	8.614	1.54112	1.5411	0
3.061	1.56326	1.5633	0	9.003	1.53824	1.5382	0
3.628	1.56190	1.5618	—1	9.186	1.53596	1.5369	+9
4.045	1.56068	1.5607	0	10.62	1.5233	1.5234	+1
4.598	1.55916	1.5592	0	13.71	1.4825	1.4822	—3
5.084	1.55773	1.5577	0	14.11	1.4709	1.4706	—3
5.602	1.55612	1.5561	0	14.50	1.4566	1.4570	+4
6.084	1.55428	1.5543	0				

The value of K is intermediate between the values of the dielectric constants of $SiCl_4$ and $SnCl_4$.

The observed and the computed values of the refractive index of $SnCl_4$, and the differences between them, are given in Table IX. The values of the constants of the formula are

Maclaurin Formula.		Sellmeier Formula.	
$a = 2$,	$K = 3.1674$,		$K = 2.4688$,
$c_1 = 0.0035364$,	$\lambda_1^2 = 0.010468$,	$a_1 = 0.020542$,	$\lambda_1^2 = 0.022754$,
$c_2 = 0.01639$,	$\lambda_2^2 = 169.65$,	$a_2 = 0.08687$,	$\lambda_2^2 = 169.65$,
$c_3 = 12.791$,	$\lambda_3^2 = 555.56$,	$a_3 = 5.9176$,	$\lambda_3^2 = 407.59$,
$c_4 = 824.35$,	$\lambda_4^2 = 7656.5$,	$a_4 = 190.68$,	$\lambda_4^2 = 806.52$.

It was necessary to assume two strong infra-red bands in setting up each formula. The value of K in the Maclaurin formula is in much better agreement with the dielectric constant, 3.2, observed by Schlundt than is the value of K in the Sellmeier formula.

The values of the refractive index computed from the two formulæ agree equally well with the observed values, for each of the five liquids. The value of K in the Sellmeier formula, however, differs from the observed value of the dielectric constant by an amount which increases with the value of the latter. The difference between the value of K in the Maclaurin formula and the observed value of the dielectric constant, on the other hand, is always less than the experimental error (2–3 per cent.) involved in the determination of the dielectric constant. The Maclaurin formula is satisfactory in each case when the value of a is 2.

The Maclaurin formula in the simplified form

$$\frac{n^2-1}{n^2+2}=\frac{K-1}{K+2}+\frac{c_1}{\lambda^2-\lambda_1^2}+\frac{c_2}{\lambda^2-\lambda_2^2}+\cdots$$

therefore represents the results of experiments on the refractive indices of liquids more satisfactorily than does the Sellmeier formula.

TABLE IX.

$SnCl_4$.

Reduced to 22.8° C.		Maclaurin Formula.		Sellmeier Formula.	
λ	n (Observed).	n (Computed).	$d\times10^4$.	n (Computed).	$d\times10^4$.
0.589	1.51007	1.5101	0	1.5101	0
0.985	1.49629	1.4963	0	1.4963	0
1.544	1.49180	1.4918	0	1.4918	0
2.030	1.49048	1.4903	— 2	1.4903	—2
2.503	1.48952	1.4895	0	1.4895	0
2.912	1.48898	1.4890	0	1.4890	0
3.361	1.48837	1.4884	0	1.4884	0
3.800	1.48789	1.4879	0	1.4879	0
4.224	1.48736	1.4874	0	1.4874	0
4.688	1.48681	1.4868	0	1.4868	0
5.258	1.48614	1.4861	0	1.4861	0
5.708	1.48554	1.4855	0	1.4855	0
6.097	1.48494	1.4849	0	1.4849	0
6.544	1.48422	1.4842	0	1.4842	0
7.059	1.48331	1.4833	0	1.4833	0
7.508	1.48241	1.4824	0	1.4824	0
8.018	1.48123	1.4812	0	1.4812	0
8.498	1.48023	1.4802	0	1.4802	0
9.062	1.47884	1.4788	0	1.4788	0
9.484	1.47764	1.4776	0	1.4776	0
10.020	1.47600	1.4760	0	1.4760	0
10.498	1.47437	1.4744	0	1.4744	0
10.969	1.47250	1.4727	+ 2	1.4726	+1
11.531	1.47013	1.4704	+ 3	1.4704	+3
11.807	1.46806	1.4691	+10	1.4690	+9
13.735	1.46217	1.4622	0	1.4622	0
14.253	1.45830	1.4583	0	1.4583	0
14.810	1.45413	1.4542	+ 1	1.4541	0
15.482	1.44869	1.4487	0	1.4487	0

No quantitative relation could be found between the wave-length of the infra-red absorption band and the combining weight, *i. e.*, the atomic weight of the base which corresponds to one atom of chlorine. The wave-length of the infra-red band, however, increases with the combining weight for the series of tetrachlorides (Table X.). The rule ap-

parently does not hold in the case of $SbCl_5$ where the valence of the base is different.

TABLE X.

Substance.	Combining Weight of Base.	Wave-length of Infra-red Band.	
CCl_4	2.99	12.64	13.16
$SiCl_4$	7.08	16.60	47.26
$TiCl_4$	12.00	21.20	
$SnCl_4$	29.70	23.57	87.50
$SbCl_5$	23.92	51.68	

The wave-length corresponding to the point of minimum dispersion for each liquid was determined as accurately as possible (error perhaps 0.1–0.2μ) by inspection of the dispersion curve. These wave-lengths were plotted as abscissæ with the corresponding combining weights as ordinates (Fig. 14). The points fall nearly upon a straight line. The wave-length of the point of minimum dispersion therefore varies directly with the combining weight of the base, whatever the valence, for the series of liquid chlorides.

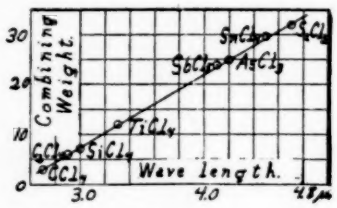

Fig. 14.

DISCUSSION OF ERRORS OF OBSERVATION.

Constant errors might be introduced by either prism, or through the adjustment of either spectrometer. The method of observation reduces the possibility of accidental error almost entirely to that involved in the estimation of wave-length.

The refracting angle of each hollow prism is probably accurate within 3″. The resulting probable error is equivalent to a variation of 6″ in the angle of incidence. The magnitude of this error was also estimated from three or four observations of the refractive index of each liquid with the 10° prism in the region in which the 40° prism was used. The difference between the refractive indices computed from the two sets of data could usually be accounted for by an error of less than 5″ in the angle of incidence on the 10° prism. Only one observation in twenty-two showed a discrepancy greater than 10″. The observations of the refractive index of CCl_4 for the D line made with the 40° prism and with the Pulfrich refractometer differed by only 0.00001.

The settings made in adjusting the spectrometer and hollow prism at the beginning of a set of observations could be checked exactly at the

end, with the exception of one observation which was sometimes uncertain by 20″–30″. The value of the refractive index is practically independent of the variation of this observation, since it affects the angle of incidence and the angle of emergence in opposite sense.

The probable error of the refractive index is thus equivalent to less than 10″ variation of the angle of incidence. The addition of 10″ to the angle of incidence increases the refractive index by 0.00006 in case of the 40° prism. The corresponding increase for the 10° prism is 0.00026–27.

The adjustment of the spectrometer used for the estimation of wave-length was checked by observation of the positions of the absorption bands of sylvite, the wave-lengths of which are given by Rubens[1] as 3.20μ and 7.08μ and of the emission band of CO_2, the wave-length of which is given as 4.40μ by Coblentz[2] and others. The deviation of each from the D-line was about 40″ too small with the spectrometer in question. After the spectrometer had been readjusted without effect, it was finally decided that the discrepancy was due to a noticeable curvature of the image of the slit. The deviation was accordingly corrected by the addition of 40″. This appears to be justified by the close agreement with the observations of Julius as to the positions of certain isolated absorption bands.

The wave-lengths corresponding to given refractive indices of rock salt estimated according to the observations of Paschen, and according to the observations of Rubens, and Rubens and Trowbridge, differ by amounts sometimes as great as 2 per cent. If the disagreement is due to experimental error, it is probable that the wave-length estimated according to Paschen's result is accurate to less than 0.5 per cent., since his observations were made with the spectrometer slits fairly narrow. If the disagreement is due to a difference in the purity of the specimens of rock salt, the wave-length estimated from the settings of the prism P may be in error by 2 per cent. or more.

The positions of the maxima of the curves (Fig. 3) from which the wave-length was estimated could be located very accurately. The uncertainty was seldom greater than 0.1–0.3 per cent. of the wave-length except in the immediate neighborhood of an absorption band.

The values of the constants in the dispersion formula are affected only slightly by a small constant error in the estimation either of refractive index or of wave-length. The error in the estimation of the wave-length close to an absorption band is such as to make the refractive index

[1] Rubens, Wied. Ann., 54, 476, 1895.

[2] Coblentz, l. c., p. 27.

appear too small on the side toward shorter wave-length, and too great on the side toward greater wave-length. This effect is illustrated in several cases in the tables showing the difference between observed and computed values of refractive index.

SUMMARY OF RESULTS.

1. The transmissivity of each of ten liquid chlorides in the region 1.5μ to 16μ was observed.

2. The refractive indices of eight liquid chlorides for a wide range of wave-lengths were determined.

3. The Maclaurin and the Sellmeier dispersion formulæ represent equally well the observed values of the refractive indices of the liquid chlorides. The value of the constant K in the Maclaurin formula is in good agreement with the observed value of the dielectric constant in each case, while the value of K in the Sellmeier formula differs by an amount which increases with the value of the dielectric constant. The Maclaurin formula is therefore in better accord with the results of experiment than is the Sellmeier formula.

4. The most satisfactory value of the constant a in the Maclaurin formula is 2. The formula may thus be used, for liquid media, in the simpler form

$$\frac{n^2-1}{n^2+2}=\frac{K-1}{K+2}+\frac{c_1}{\lambda^2-\lambda_1^2}+\frac{c_2}{\lambda^2-\lambda_2^2}+\cdots.$$

5. The wave-length of the strong infra-red absorption band increases with the combining weight of the base, for the series of tetrachlorides. The relation appears not to hold for bases of different valence.

6. The wave-length for which the dispersion is minimum is approximately proportional to the combining weight of the base, whatever the valence of the base.

I take this opportunity to thank Dr. R. C. Maclaurin and Dr. E. F. Nichols, at whose joint suggestion the present investigation was undertaken, and Professor A. P. Wills for their kindly interest and many helpful suggestions during the progress of the work. I wish also to thank the Rumford Committee of the American Academy of Arts and Sciences for the use of the spectrometer which they placed at my disposal, and upon which the rock salt prism was mounted.

PHŒNIX PHYSICAL LABORATORY,
November 28, 1911.

THE DISTRIBUTION OF CURRENT IN POINT-PLANE DISCHARGE.

By Robt. F. Earhart.

A CRITICAL examination of the appearance of the luminous discharge in tubes of moderate vacuo will show that small changes in pressure and potential will produce great differences in luminosity under some circumstances. This is particularly true when one of the electrodes is a plate and the other electrode a point or small sphere. In the region of the critical pressure for the distance separating the electrodes the variations are quite rapid. In case the plate is made the cathode there is a limited range of pressures where a change of one per cent. in potential will convert a feeble insignificant discharge confined to a limited part of the plate into a brilliant discharge in which a large area of the plate is covered with a luminous layer of gas, the current increasing many fold.

The purpose of the present investigation was to study, so far as time and circumstances would permit, the variations in intensity of current with pressure, potential and distance but especially the distribution of current. To this end the author has studied experimentally the distribution over a plate of the discharge occurring between what may by courtesy

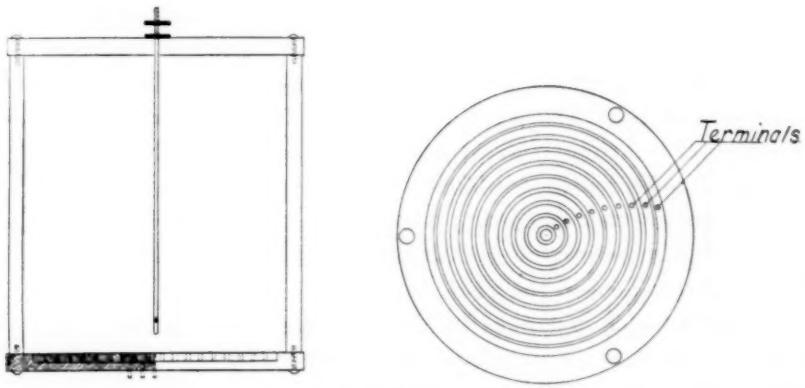

Fig. 1.

be called a point and that plate for five distances, viz., .5 cm. 1 cm., 2 cm., 3 cm., 4 cm., and for several voltages. There is no especial difficulty in obtaining such results so long as the point is made cathode, in which

case the currents are comparatively small; however, the experimental difficulties are greatly increased if the plate is made cathode and a wide range of pressures is to be studied.

Fig. 1 illustrates the general form of the apparatus.

Nine brass rings were mounted concentrically about a brass rod or core. These were set into a rubber plate. The areas of the conducting zones are given in the accompanying table. The zones were of equal width, five mm., each one being separated from its neighbor by a ring of rubber insulation two mm. wide.

Ring. No.	Area. Sq. Cm.
1	.196
2	1.885
3	3.770
4	5.655
5	7.540
6	9.425
7	11.310
8	13.195
9	15.080
10	16.965

It would undoubtedly be an advantage to have more rings of less width and the insulation rings much thinner but difficulty in the mechanical construction made this seem inadvisable. Connection with each ring was made by means of a heavy brass pillar extending through the bottom of the hard rubber disk. The disk was mounted on insulating supports and electrical connections with each ring made by soldering wires to the terminal pillars. These leads were brought to a terminal board and were each connected to ground through a small resistance. The resistance in each case was equal to that of a shunted galvanometer used to measure current. The terminal board was so arranged that the shunted galvanometer might replace the blind resistance in any of the circuits without interrupting the current passing through any other circuit. It was therefore possible to determine the current passing through any of the rings which together formed the plane surface.

The point which is designated thus in order to distinguish it from the plane, consisted of a hemisphere turned on a platinum rod of one mm. radius. In some preliminary experiments this hemisphere projected through a hard rubber plate which was properly spaced from the plane. Under these circumstances it was noticed that a conducting deposit soon formed about the point when it was cathode and that when a discharge continued over several hours, this deposit increased perceptibly

both in area and thickness. This, while it did not seem to affect greatly total discharge, did modify the distribution of the current. On this account the plate supporting the point was elevated some 16 cm. from the plane and connection with the platinum hemisphere made through a brass rod terminated by the platinum cylinder. The entire rod was then jacketed with a glass tube drawn thin near the lower end, leaving only the platinum hemisphere exposed. In time the tip of the glass envelope would become coated with a deposit but the distribution of the field was not seriously affected. It was only after prolonged use that the effect of this deposit became apparent. That some modification of the field due to the presence of the deposit will progress from the start is probable.

A glass bell-jar covered the entire discharge apparatus. The connection to the upper rod was made through a hole in the top of the receiver and was sealed in with cement. Pressures were made with a McLeod gauge. Since the capacity of the bell-jar was large it was possible to reduce the pressure by as small increments as desired or to increase the pressure by small amounts. The latter operation was effected by admitting small quantities of air trapped between two cocks connected in series with an external supply of dry gas.

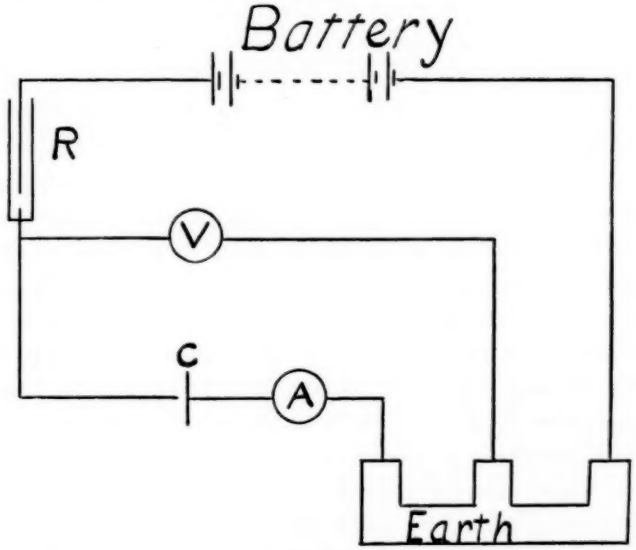

Fig. 2.

The general plan of controlling and observing potential differences is shown in Fig. 2.

A battery of 450 small storage cells supplied the E.M.F. The potential

between point and plane could be regulated by the amyl alcohol cadmium iodide resistance (R). This potential difference could be measured by means of the Weston voltmeter (V) with a suitable multiplier in series which was connected between the point and earth. It may be noted here that the potential of the plate was zero and that the potential measured was always that existing between the point and earth. No correction was deemed necessary for the very slight difference in potential between the rings and earth due to the resistance of the lead wires and the current measuring system (A) because these were small compared with the effective resistance of the discharge gap (C). In obtaining the results which are hereafter given, certain precautions were necessary. Failure to observe these in some preliminary experiments gave rise to inconsistent values. Air was the only gas used in this series of measurements. It is necessary that the air be thoroughly dried. This was easily accomplished by pumping down to the initial pressure desired and allowing the air in the receiver to remain twenty-four hours or longer before experimentation began, a tray of phosphor pentoxide being placed under the receiver. In case air was admitted to increase the pressure, it was drawn from a system containing a dust filter and drying reagents. While this removed water vapor it was noted that fresh gas always gave larger current values than after the discharge had continued for some time. The conditions here presented for a chemical change to take place in the air are favorable and this may be the cause in the decline in conductivity. Some experiments were made by Mr. F. W. Pote, of this department, with whom the author collaborated during the preliminary portion of these experiments, on the change of current with time. Mr. Pote found that the current declined with time of discharge but that after a half hour the rate of decline became very small. It might be argued from this that with no fresh gas entering, rate of combination would be simply a function of the time. However, practically the same state of affairs exists when nitrogen is substituted for air, and while the purity of the nitrogen might well be doubted, the removal of water vapor, oxygen and carbon dioxide in part at least, would diminish the chemical action. Whatever may be the cause of this change in conductivity my observations show that the current passing through a thoroughly dried air when fresh may exceed by 50 per cent. the value obtained after being subject to discharge When a set of observations were to be taken, the discharge was continued for a half hour before experimentation was begun and when fresh gas was admitted even though the pressure was changed by a small amount, ten or fifteen minutes elapsed before readings were taken. This greatly increased the tediousness of the operation but

it was only by adopting a plan of this kind that uniform and consistent results could be obtained. Taking these precautions it is possible to reproduce results from day to day with an agreement of a few per cent. Whatever consistency may appear in tables and graphical representation is due, in my opinion, to lack of haste in taking observations. There is something in a fresh gas that makes it a better conductor than a gas which has undergone continued discharge. In this I am only emphasizing statements made by others working on related lines.[1]

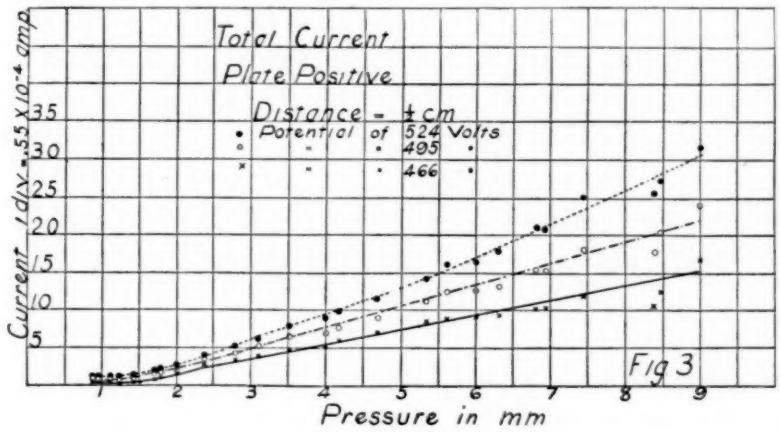

Fig. 3.

Figs. 3, 4, 5 and 6 indicate in part the results obtained when the point was made negative. Only the total current is indicated in these graphs. All of the data were secured showing the distribution of the current at the

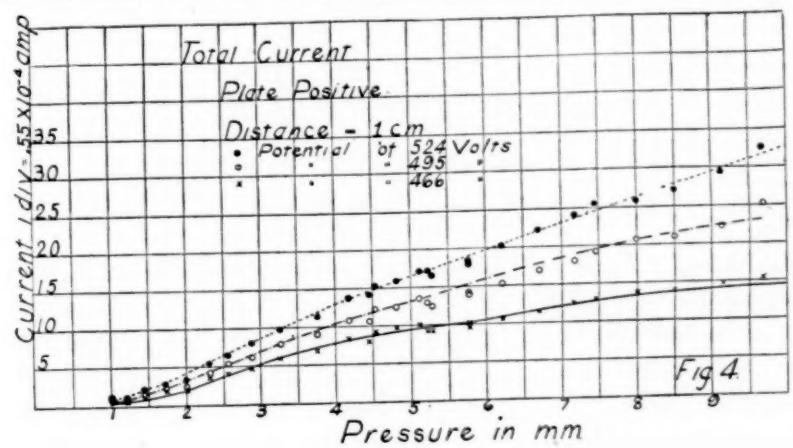

Fig. 4.

several voltages and pressures for the distances given, viz., .5 c.c., 1 cm., 2 cm. and 3 cm.

[1] A. B. Meservey, Phil. Mag., 21, p. 479.

The values shown are merely the sums of the current readings for the rings functioning in the discharge. It was not feasible to take current readings at pressures lower than those indicated for this extended the pressures well below the critical pressure Here, as is well known, the

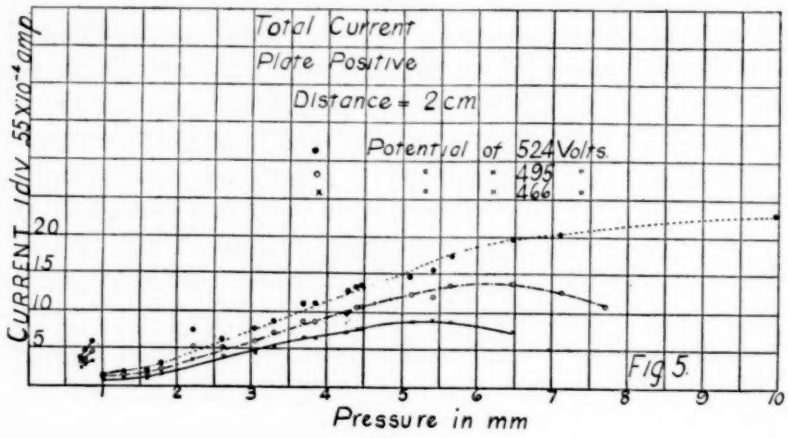

Fig. 5.

potential required to produce and maintain a discharge increases rapidly. In the case represented by Fig. 3, where the distance separating point and plane is .5 cm., the readings were extended to pressures of 2.5 cm. Hg, although the data shown on the plate do not extend beyond 1 cm.

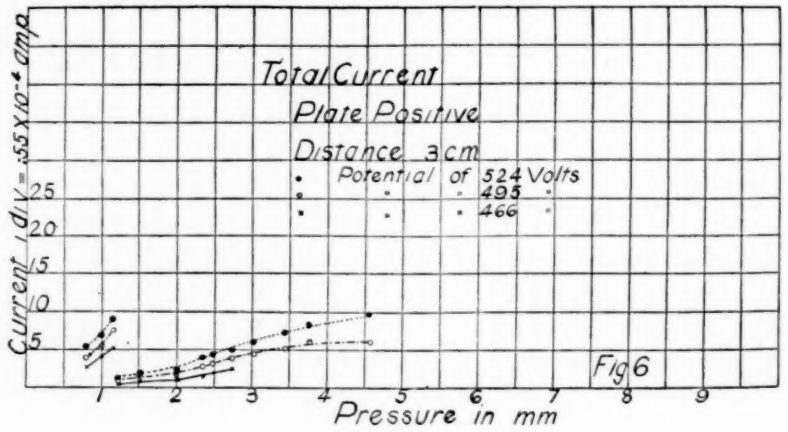

Fig. 6.

At a pressure slightly greater than 2.5 cm. the potential of 464 volts is not sufficient to maintain a discharge. The general form of the complete curve is similar to that shown in Fig. 5 for a 2 cm. distance. Above the critical pressure there is a gradual increase in total current with

pressure until a maximum is attained, then for a considerable range in pressure a negligible change in current. As the pressure is approached at which the potential is insufficient to maintain discharge there is a decrease in the value of the current. The maximum referred to does not come at the same pressure for all voltages. In general the higher the voltage the greater is the pressure at which the maximum is reached.

Fig. 7 shows the distribution of current for a case which is fairly typical

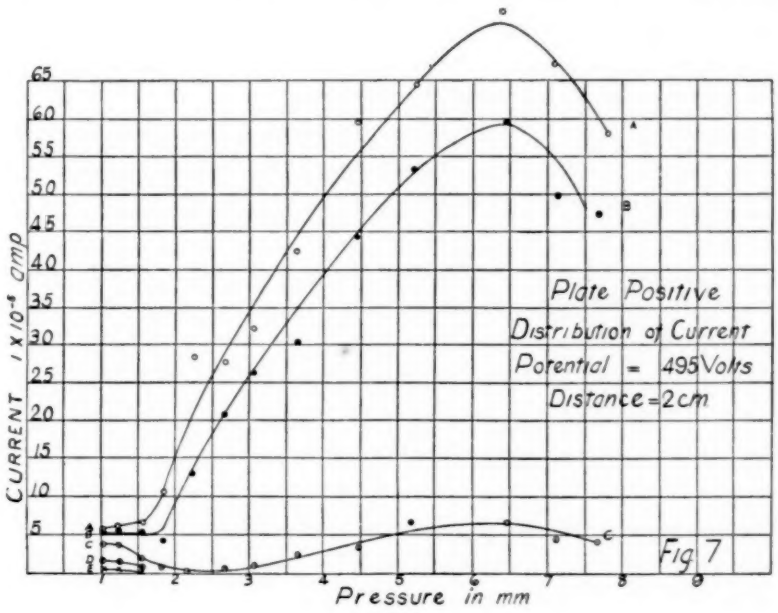

Fig. 7.

of all distributions for point negative. This figure indicates the distribution for a potential of 495 volts, the distance being 2 cm. The vertical distance between the lines *A*, *B*, *C*, *D*, *E* shows the value of the current for the inner ring together with rings 2, 3, 4 and 5 as measured from the center outward.

In Figs. 5 and 6 a discontinuity appears at the critical pressure. This corresponds to a decided change in the appearance of the discharge. For the lower pressures the cathode glow is visible, the first dark space and surrounding this a faint negative glow is visible Most of the current is carried by the third, fourth and fifth rings in this stage. When the critical pressure is attained, the outer mantle of luminous gas is no longer visible and the fourth and fifth rings bear a negligible current, the inner rings carrying most of the discharge. As the pressure is increased the first and second rings bear an increasing proportion of the current. It

should be remembered that the area of the second ring is approximately ten times that of the inner core. In a darkened room it is possible to observe a cone of luminous gas spread out with increase in pressure until the third ring begins to receive a larger portion of the current. After the maximum value has been passed the discharge is concentrated more and more in the region directly beneath the point. For the three cm. distance (Fig. 6) the first three rings served about the same purpose as the two inner ones for the two cm. distance, while for the shortest distance (a half cm.) the inner core played the most important rôle in carrying the discharge. The comparatively large width of the zones and of the insulation rings prevented further refinement.

In general, it may be said that for pressures exceeding the critical pressure the area of the plate functioning in the discharge is limited to a small solid angle while for pressures less than the critical pressure a larger portion of the plate comes into play.

Measurements on the distribution were also taken when four cm. separated the electrodes. Here the lower voltages used in the previous cases would not suffice to maintain a current over an extended range in pressure, the higher potential difference 524 volts giving only a small current. This is shown in Fig. 8 drawn to a different scale and is used

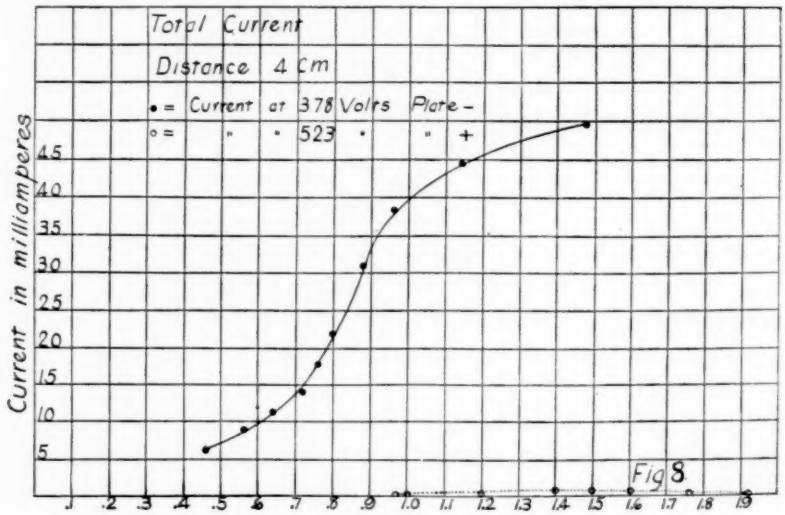

Fig. 8.

to compare the magnitude of the discharge for point cathode with plate cathode.

It should also be noted that while the current for the plate cathode is much greater, the potential is lower than that used to maintain the dis-

charge from the negative point. It would be more appropriate to compare currents at the same potentials but the potentials which would merely sustain a measurable discharge from a negative point would produce currents so great when the polarity was reversed that the capacity of the battery would be exceeded for an extended set of observations and indeed would become inconveniently large.

Before passing from the discussion of the discharge from the negative point it may be well to state that for the higher pressures the potentials used would not start a discharge but were sufficient to maintain it. It was necessary in many cases to start with a discharge produced at a pressure not far removed from the critical pressure and proceed by small increments to the higher pressures, keeping the potential constant meanwhile. The minimum potential required to produce a discharge from the negative point is 350 volts or thereabouts at the critical pressure and a potential not very different from this will maintain a current at higher pressures. The increase in potential necessary to maintain a current increases very slowly with increase in pressure for a time and then increases quite rapidly. The greater the distance separating the plates, the more rapid is the increase. I have found, for example, that when the electrodes were separated 1 cm. the potential required to maintain a discharge at 10 mm. pressure in air is 408 volts. When the separating distance was .5 cm. a potential of 464 volts would maintain a current for a pressure of 26 mm., however when the distance was 4 cm. 464 volts would not sustain a current when the pressure exceeded 2 mm.

It was found much easier to start a discharge with the point negative than with plate negative but that once the discharge had started a somewhat lower potential would suffice for maintenance when the plate was negative. In fact the usual method employed when the plate was cathode was to produce the discharge with the point negative and then by means of a reversing switch to interchange the polarity of the electrodes.

Before discussing the currents produced when the plate was cathode attention should be called to the difference in scale employed. In Fig. 8 the current for the interchanged polarities is plotted to the same scale for sake of comparison. Here 1 division equals 1 milliampere. The pressure is given in tenths of millimeters.

Comparing the currents for plate cathode it may be noted that for the same potential and pressure the current is greater when the distance, separating the electrodes is 4 cm. than for the smaller distances, throughout the range in pressure over which the observations extend.

Fig. 10 shows the distribution of the maximum current produced at

different pressures. The vertical distance between the two upper lines 10 and 9 indicates the current in milliamperes carried by the outer ring: the distance between the lines 8 and 9, the current carried by the ninth ring, etc. The total current is also shown by the position of the upper

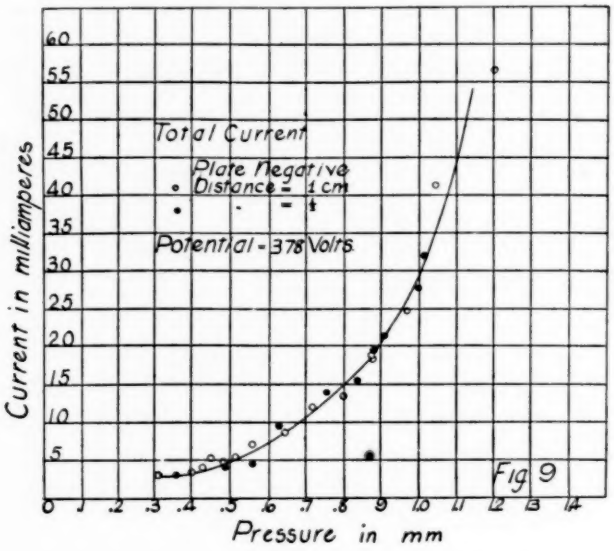

Fig. 9.

curve and is comparable with the curves showing total current in Figs. 8, 9 and the upper curve in Fig. 11. The individual readings on which this family of distribution curves is based are shown by distinguishing symbols so far as space on the drawing would permit.

The lines extrapolated are not mere extrapolations but are based on quantitative data no less consistent than those shown. In the portion of the plate where the family of lines converge, the curves as well as readings are omitted to avoid crowding. The graph indicates that at lower pressures, where the current is small, all parts of the plate take part in the discharge, and with increase in pressure, the current increases over all portions of the plate but that the rate of increase is greater on the outer zones.

Fig. 9 shows the total current for distances of both .5 cm. and 1 cm. For the range in pressure covered there is little or no difference in total current, although the distribution is not the same. For the smaller distance the outer rings bear slightly less current than for the greater distance. When discharge occurs, there is a bright layer of luminosity about the anode and a layer of luminous gas appears over the plate. This luminous mantle is not in contact with the plate but a centimeter

or more above it, depending in part upon the pressure. In the case of the point spaced .5 cm. from the plate, the exposed point was well underneath this luminous layer and for the 1 cm. distance just within the luminous mantle. For the greater distances the point was plainly above the layer. I conclude from this that if the anode is within this layer of

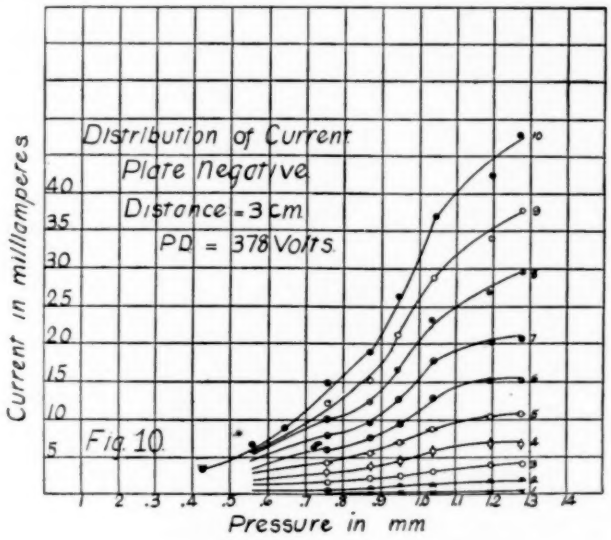

Fig. 10.

luminous gas, the quantity of gas functioning in the discharge is not changed with the distance of the point from the plane; for the position of the luminous layer does not seem to vary when the anode is within this region. If the mass of gas functioning is the same in the two cases then equal potentials would give the same currents.

Figs. 11 and 12 considered together show that the silent discharge in moderate vacuo bears some points of resemblance to the electric arc. In general, there may be two values of the current under the same potential and pressure. The potential difference between the electrodes is a function of the current between these electrodes. If a discharge is started there are two ways of varying the potential. Let us assume that a moderate current is passing across the gap and that the potential is to be raised by altering the resistance in the external circuit. A decrease in the external resistance may have the effect of increasing the current and thus cause a decrease in the potential across the gap. Further decrease in resistance may cause a fall in potential across the gap. This process will continue until a critical value is reached when throwing more of the E.M.F. of the battery across the gap will cause a rise of both current and potential. If this stage is reached and the external resistance

be then increased both current and potential will fall until the previous critical value is attained; further increase in resistance has the effect of cutting down the current rapidly but makes small changes in potential. Finally with diminution of current the potential rises. During these changes there is, however, a redistribution of the current over the plate. This would mean that a different quantity of gas was functioning in the

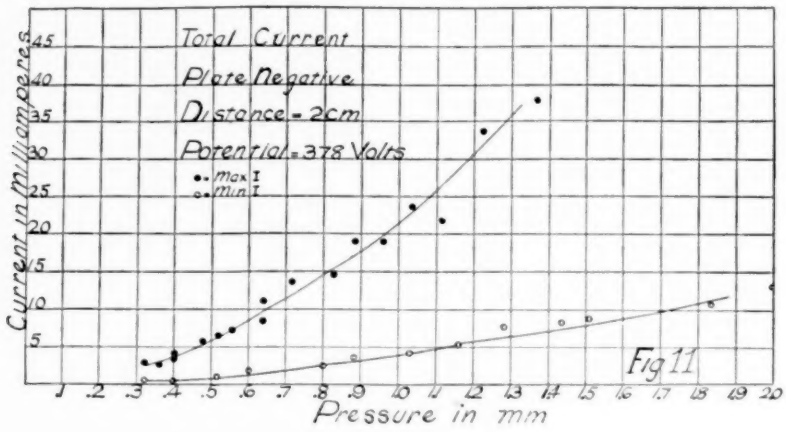

Fig. 11.

two cases and that the effective resistance would be changed. We might expect then with the same potential difference and different effective resistances to have different current values. In Fig. 11 two curves are shown, the upper one indicating the maximum values for current. This is stable and the distribution over the plate was obtained. It is similar to the typical case shown in Fig. 9. With increase in pressure the rate of increase over the outer zones increases at a more rapid rate than over the inner zones.

The distribution for the minimum current could not be satisfactorily obtained at all pressures. Corresponding to any potential there is a pressure at which both discharges are stable. For the maximum current the entire plate is covered with a beautiful mantle of luminous gas. In the second stage the discharge is confined to the inner rings. It is insignificant in appearance and the current is small, but in passing from one stage to the other and while the current is gathering in toward the center there is a very unstable condition. The appearance of the luminous patch is not always symmetrical and it is in constant motion. By connecting all the zones in parallel the total current could be obtained but the distribution seems to vary constantly and could not be obtained for all the pressures shown. Both maximum and minimum curves are shown in Fig. 11. The lower branch of the curve was carried to pressures higher

than those shown in the figure, but is merely an extrapolation of the current line shown.

No doubt a similar state would occur for point negative but with the limitation of the battery and resistance used only one limb of the current curve could be followed.

With a sufficient number of cells it might be possible to increase the potential difference until a discharge of a different character occurred accompanied with greatly increased current. This might take the form of a disruptive discharge in which the greater current would be accom-

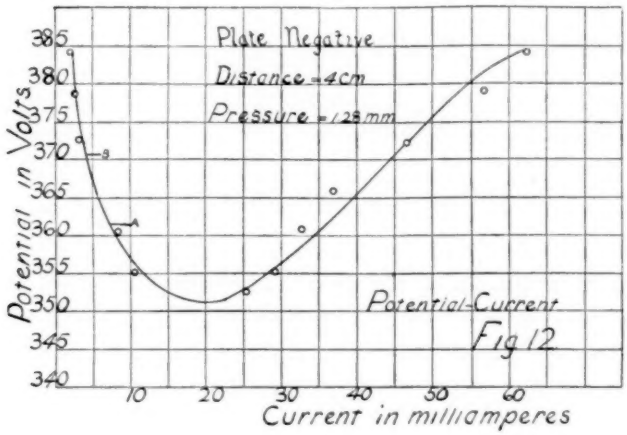

Fig. 12.

panied with a lowering of the potential. During such transition the potential would undoubtedly pass through the values used in this experiment and while it might be difficult or impractical to measure the magnitude and distribution of these currents it is probable that a second value would be obtained. In the assumed case the intense portion of the field is concentrated near a point while in the case where measurements were taken there is opportunity for readjustment of the electric force over a wide surface. Perhaps it is this which has made possible the observations over both branches of the current curve throughout the pressure range studied.

Fig. 12 shows how the total current curve varies with the potential impressed between the electrodes.

The table which accompanies this indicates the distribution of the current while the changes take place. Beginning with the maximum current at 383 volts, the current decreases with decrease in potential until a potential of 352 volts is reached. The table indicates that the decrease takes place more rapidly on the outer zones; the discharge, however, is stable. From the points marked *A* and *B* on the curve and while the

luminosity is drawing in to the central region, the condition is unstable and values were not obtainable. At slightly higher potentials the current became stable and was confined to the central portion of the plate.

Current in Milliamperes.

Volts.	1	2	3	4	5	6	7	8	9	10	Total.
384	.09	.62	.73	.32	.04	.02	—	—	—	—	1.84
378	.13	.69	.99	.50	.15	.03	—	—	—	—	2.49
373	.10	.66	.96	.80	.64	—	—	—	—	—	3.16
361	.08	.62	.66	.64	.73	.85	.99	1.18	1.33	1.50	7.58
355	.09	.60	.83	.88	.94	1.03	1.20	1.50	1.88	2.10	10.90
351	.13	.92	1.27	1.62	2.17	2.74	3.28	4.07	4.55	4.90	25.65
352	.15	.84	1.27	1.63	2.20	3.05	3.80	4.75	5.40	6.07	29.16
365	.19	1.05	1.48	2.20	2.68	3.25	4.40	5.20	5.90	6.80	33.15
367	.20	1.14	1.72	2.34	3.00	4.50	4.65	5.57	6.64	7.70	37.46
373	.24	1.55	2.00	2.82	3.80	4.20	5.72	6.60	8.44	11.20	46.51
378	.24	1.62	2.60	3.65	5.07	5.72	7.30	7.90	10.30	11.90	56.30
384	.20	1.28	2.34	3.45	4.90	7.00	8.35	10.10	10.90	13.60	62.12

The curve shown is the total current curve obtained by adding the values of current shown by the individual rings. The theoretical potential current curve for an arc is shown on page 617, second edition of Sir J. J. Thomson's Conduction of Electricity through Gases. The equation for the curve is that of an hyperbola to which the curve in Fig. 12 bears a close approximation.

Under some conditions I have found that the lower portion of this curve is much flatter than the one shown. Starting with a small current and throwing more of the E.M.F. across the gap produces little noticeable change in the potential but serves merely to increase the current. Under such circumstances a rise in potential of 2 or 3 volts in 350 will convert a feeble discharge into one of great brilliancy with corresponding increase in current.

After a continued discharge the plate became much heated. The zones were of such generous dimensions that this could not be due to a Joule effect but was due no doubt to the bombardment of the cathode.

Some experiments with higher potentials were attempted and while they perhaps possess some points of general interest, are not reliable from a quantitative standpoint.

During the preliminary portion of this experiment, the author was assisted by Mr. F. W. Pote, of this department, with whom a joint preliminary report was made in the November, 1910, meeting of the American Physical Society. The present paper is an extension of that work.

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THE EFFECTIVE DEPTH OF PENETRATION OF SELENIUM BY LIGHT.

By F. C. Brown.

RECENTLY it was shown that[1] the changes of conductivity in a certain variety of selenium could be explained quite accurately by assuming that the light penetrates throughout the conducting layer and that it produces two changes in the selenium. If, therefore, the light action takes place in only a very small portion of the conducting layer, it might be necessary to recheck theory and experiment. The principal object of this investigation was to get the effective depth of penetration in order to be more certain of the theory. Incidentally the results give some information bearing on the nature of the process of absorption in this variety of light-sensitive selenium.

Theoretical Considerations.

The measurements on the depth of penetration depend on the similarity of heat and light action in selenium. In fact in so far as temperature changes do not produce effects in the selenium identical to the light changes, the results will be in error. The reasons for assuming the identity of the two actions will be given in a succeeding paragraph. The theory is much simplified by calculating with conductivity relations rather than with the resistance relations. In fact I believe that many times we are handicapped in theoretical considerations by placing too much emphasis on Ohm's Law. Further the theory requires a second assumption, which is that temperature changes take place throughout the conducting layers of selenium alike everywhere. The results will be indirect in that they depend on the two assumptions just mentioned. Naturally, if light acts the same as an increase of temperature, we should expect that the absolute amount of change in the conductivity, by a light of constant intensity, would diminish as the temperature of the selenium rises. Thus if a curve is plotted showing the absolute change of conductivity, ΔC, for the various values of the conductivity, C, we have the relation between C and ΔC regardless of the depth of penetration of

[1] Paper by Brown on "The Recovery of the Giltay Selenium Cell and the Nature of Light Action in Selenium."

the light. Suppose the curve in Fig. 1 to represent such relations as just mentioned. Suppose the conducting layer of selenium at temperatures T_1, T_2, T_3, etc., to have conductivities of C_1, C_2, C_3, etc., respectively, at the various temperatures. The amount of change in conductivity by the standard light, or the absolute sensibility, is given by the ordinates at

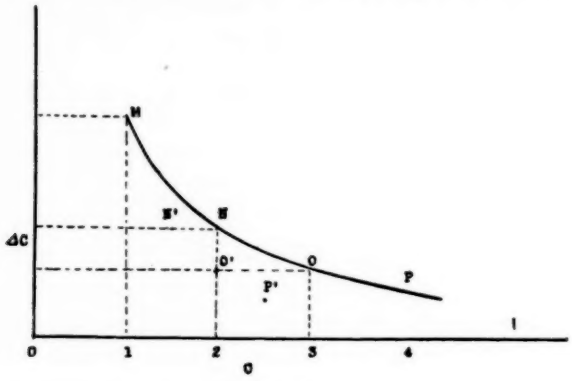

Fig. 1.

the points M, N, O and P for the same temperatures. However the absolute sensibility is given as a function of the conductivity prevailing before the standard light illuminates the selenium. Temperature changes are introduced only as a means of producing uniform changes in the conductivity that reach to the bottom of the selenium. For the sake of argument, consider the selenium divided into two imaginary layers of equal depth. The plane of these layers is taken perpendicular to the direction of the impinging light. We consider that the effect of the light is everywhere uniform in the top layer, and that there is no action whatever by the light in the lower layer.

The ordinate at N shows the sensibility, ΔC, when the initial conductivity has been doubled. If however the initial conductivity is doubled by light action from a second variable light source, *i. e.*, the intensity of the light is varied until the desired conductivity is attained at the equilibrium condition, then the part of the selenium affected by the light must have been trebled; for

$$C = \tfrac{1}{2} + 3 \times \tfrac{1}{2} = 2.$$

But the curve M, N, O, P shows that if the region affected by light is trebled that the sensibility is only what is represented by the ordinate at O. The meaning of this is that if light is used to produce the initial desired conductivity which is double that in the dark, then the point on the sensibility curve will drop from N to O'. Exactly the same method of procedure will locate the points N' and P', so that we are enabled to plot

the sensibility curve M, N', O', P', for the selenium when the initial conductivity is altered solely by light. Now if it is found experimentally that the sensibility represented by the curve M, N, O, P, when the initial conductivity is changed by the temperature of the selenium, and if the experiments show that the sensibility is represented by the curve, M, N', O', P', when the initial conductivity is changed by light, it can be concluded that the effective depth of penetration is one half the total depth of the conducting selenium. However, if the experimental sensibility curve, when all changes are produced by light, lies between the two curves mapped out in Fig. 1, it is to be concluded that the effective penetration is greater than the half depth, and if the experimental curve lies on the other side of M, N', O', P', the penetration is less than the half depth. Just what fraction of the selenium is penetrated by the light can be determined by finding the theoretical curve that matches the experimental curve. This cut and try method of fitting is not as difficult as it might seem. A very little work will approximately locate the theoretical curve that matches the observations. Other curves may be located in the same way that the one passing through M, N', O', P', was located.

If the two basic assumptions should be seriously in error, then it might be impossible to match any of the experimental curves with any of the theoretical curves. The curves would not be of the same character, and consequently they would cross each other. The likeness or unlikeness of the character of the experimental and theoretical curves is evidence for or against the original assumptions.

The Similarity of Heat and Light Action.

The experiments are based on the similarity of heat and light action in selenium. In 1908 it was suggested[1] that increased temperature and illumination each seemed to take the selenium toward the same equilibrium state, and it was inferred that heat and light produce the same kind of change in the selenium. Later by a study of the change of conductivity with time when certain selenium cells were suddenly heated or illuminated, MacDowell[2] concluded that the "action of light and heat in producing change in conductivity in selenium are apparently identical." More recently in an analytical investigation of the time changes in the Giltay cell,[3] it was shown that so far as light action is concerned heat alters the direct rates α_1 and β_1 in about the same ratio as does weak illumination and in addition produces a minor change in the reverse rate

[1] Paper by Brown and Stebbins, PHYS. REV., XXVI., p. 273, 1908.

[2] Paper by Miss Louise MacDowell, PHYS. REV., XXXI., p. 524, 1910.

[3] PHYS. REV., XXXII., p. 403, 1911.

β_2. A further study of the heat changes in selenium indicates with considerable certainty that heat produces the same very rapid and very slow changes as light, and further that there are one or more minor changes that are not caused by light. The first assumption then will be slightly in error owing to the inexact identity of light action and heat action.

The curves in Fig. 2 show the changes in conductivity when the Giltay selenium cell was suddenly changed in temperature. Curve (*a*) shows the change when the temperature was suddenly raised from 25° C. to

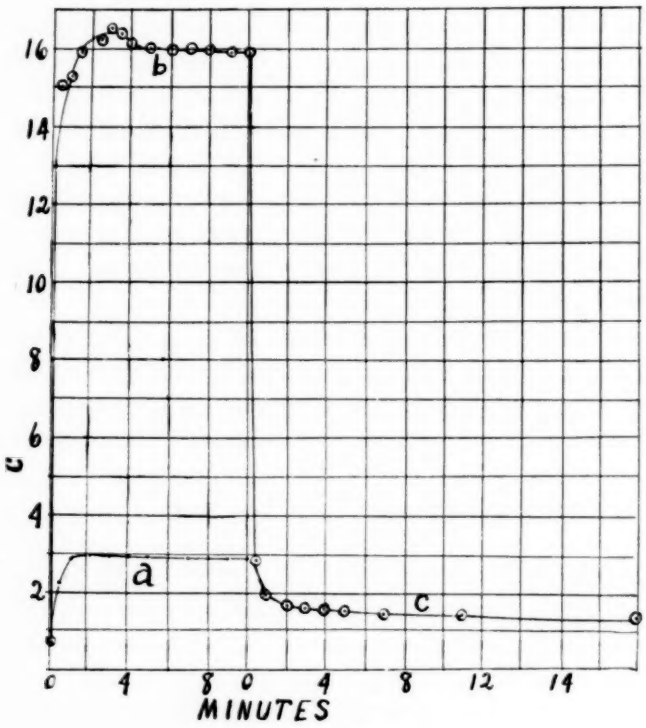

Fig. 2.

Curve (*b*) shows the change of conductivity of Giltay cell when the temperature was suddenly raised from 25° C. to 93° C. Curve (*c*) shows the change when temperature change was of the same magnitude but in the opposite direction. Curve (*a*) is for the sudden change of temperature from 25° C. to 53° C.

53° C. by plunging the cell in a kerosene bath at the higher temperature. Similarly curve (*b*) shows the changes when the cell was suddenly plunged in a bath at 93° C., and curve (*c*) is for the recovery when the cell was returned to the bath at 28° C. If these curves are compared with corresponding exposure and recovery curves for light as shown in Figs. 2 and 3

of my former paper[1] it will be observed that there is a striking similarity. For either light or heat about 95 per cent. of the change takes place in less than 30 seconds. It is impossible to be very certain about what portion of the change by heat takes place in very short intervals of time, because of the time required for the selenium to arrive at uniform temperature. Consequently it is impossible to assign proper rates of change to explain the curves obtained in going from one temperature to another. However a careful study has convinced me that while temperature changes produce effects identical to the effect by light, there is also an additional effect of minor importance which is not covered by our theory.

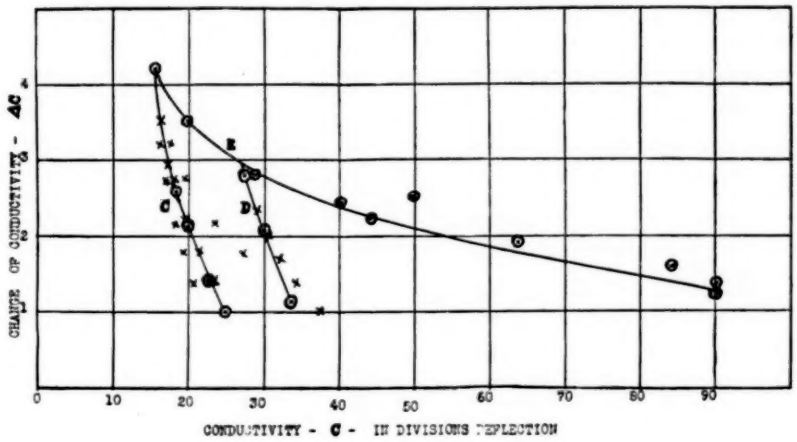

Fig. 3.

This is not manifest in the exposure curve, but the recovery on going from the higher to the lower temperature is very slow, requiring many hours to arrive at the equilibrium value, and the conductivity can not be represented everywhere by an equation having only the sum of two exponential quantities, such as I have presented previously to represent light changes. This lag may arise from changes in pressure on the selenium, arising from a slow changing of shape of the stone form or the wires which are parts of the selenium cell. In fact I think this explanation is very plausible for that small part of the conductivity change which is not covered by our theory.

A similar very slow and very small change in the conductivity has been observed at temperatures above 50° C. by Mr. Ernest Dieterich. After the selenium had been heated to a uniform high temperature for more than an hour and had become apparently constant, it began to increase its conductivity in a rather irregular fashion, the rate being smaller at first,

[1] PHYS. REV., XXXII., p. 406.

reaching a maximum after several hours, and then becoming zero. The total amount of this increase was not more than 10 per cent. of the original conductivity. This too was probably due to an annealing process taking place in the stone cell form. Such a change as the one just mentioned might minimize the falling off of conductivity with heating such as occurs after two or three minutes. It must be understood however that this falling off by temperature rise is not at all necessary in order that light action and temperature action shall be alike, and further that all these dissimilarities are small comparatively and of minor importance.

EXPERIMENTAL ARRANGEMENTS.

The selenium that was used in this investigation was that of the same Giltay cell heretofore mentioned. The selenium was crystallized between two parallel wires of 0.16 mm. diameter would around the flat stone form. The average depth of the selenium was estimated to be not less than 0.08 mm. and not more than 0.14 mm., the most probable value being 0.11 mm. The cell was placed in a large kerosene bath with stirrer. The temperature of the bath was regulated by an electric heating coil placed in it. Two miniature incandescent lamps inside a beaker were sunk in the kerosene at a distance of about 15 cm. from the selenium. One of the lamps was regarded as a standard and it was always regulated to give a constant light intensity by adjusting the heating current to 0.32 ampere. The second lamp was regarded as a variable light source, and its intensity was regulated by the current so as to produce desired values of the conductivity of the selenium. The intensity of these lights was at all times small compared to a standard candle at a distance of a meter. As there seemed to be no reason for knowing their candle power it was not determined.

The conductivity was measured directly by a Siemens and Halske needle galvanometer in series with the selenium cell. Its sensibility was approximately 2×10^{-7} amperes per division and its resistance was 220 ohms. The range was suitably altered by a shunted resistance.

In these experiments we always intended to measure only the equilibrium values of the conductivity. Consequently the rates of change were observed only with a rather general interest.

THE RESULTS.

The manipulation was quite simple, and can be clearly understood by studying the accompanying Table I., which gives a sample of the observations. A glass heavily coated with anilin blue was placed in the beaker with the lamps so that an approximately monochromatic illumina-

tion of the selenium might be obtained. The conductivity in the dark, C_d, was first measured and then the cell was exposed to the standard light, l, by closing the lamp circuit with 0.32 ampere. Thereby the conductivity increased by an amount ΔC and reached the equilibrium value C_1. After the selenium had recovered its conductivity in the dark, C_d, it was exposed to such a faint illumination from the second lamp that the equilibrium conductivity assumed the desired value C_L. Then the selenium was simultaneously illuminated by the standard, and the conductivity increased to the value C_{L+1}. And so on the variable light was increased step by step while the standard remained fixed.

TABLE I.

Observations with Blue Light.

Time of Observation.	Temperature, Degrees Centigrade.	Conductivity in Dark, C_d.	C_L	C_1 or C_{L+1}	ΔC	C
	21.3	15.3	15.3	17.7	2.4	15.3
	21.5	"	17.8	19.2	1.4	17.8
11:13–11:32 A.M.	"	"	16.4	18.4	2.0	16.4
12:10–12:25 "	"	"	20.0	21.1	1.1	20.0
12:50– 1:05 P.M.	"	"	24.0	24.6	0.6	24.0
2:35– 2:50 P.M.	35.8	29.0	——	30.5	1.5	29.0
3:55– 4:10 "	41.6	38.3	——	39.8	1.5	38.3
5:00– 5:10 "	45.6	47.1	——	48.2	1.1	47.1
5:23–	45.6	47.1	——	——	—	——
5:55– 6:02 "	——	44.7	——	45.9	1.2	44.7
7:50– "	——	43.3	——	44.5	1.2	43.3
8:00– A.M.	24.0	18.4	——	20.5	2.1	18.4
10:40–11:02 "	37.0	31.3 30.3	——	32.4	1.6	30.8

By obtaining sufficient data of this kind, it was possible to plot the sensibility-conductivity curve, A, shown in Fig. 4. This curve merely shows the absolute amount of change of conductivity, ΔC, when the selenium has various initial conductivities. It is understood, in this instance, that the initial conductivity is varied solely by illumination. When the initial conductivity was varied solely by temperature changes, the absolute amount of change by the standard light was not

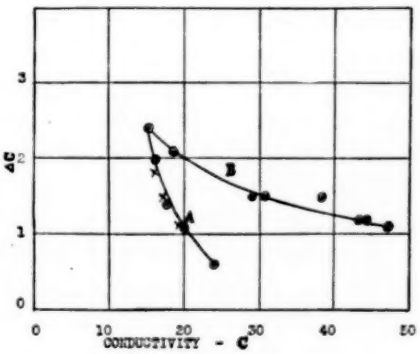

Fig. 4.

notably different as shown in the table and also by curve B, of Fig. 2. Considering the possible sources of error, the points lie on a curve as nearly as could be expected. The value of ΔC when C was 38.3 is manifestly too large. Possibly the conductivity was increasing due to temperature action during exposure. It is unfortunate that the conductivity in the dark could not always have been read both before and after exposure to light.

In a similar manner to that just described were the data taken for the absolute sensibility when the selenium was illuminated with red light. Curve C in Fig. 3 gives the sensibility when the conductivity was varied by the variable light, but there is a decided difference in the magnitude of the change by the standard light. This is no doubt due to the greater effectiveness of red light in causing change of resistance of selenium.[1] The current in the standard lamp was kept at 0.32 ampere at all times. The curve D was obtained from data taken in the same way as those for curve C, except that the initial conductivity was kept at $C_d = 27.5$, by keeping the temperature of the cell and its bath at 32° C. The observations shown in curve E were obtained as were those in curve B of Fig. 4. They are not particularly good but at the higher temperatures a number of difficulties made it hard to obtain the increment of conductivity by the standard light and at the same time keep other conditions fixed. It is believed that the temperature rise during exposure would account for some of the high values obtained.

In working up the results the method of procedure is to assume different depths of penetration and to solve for the corresponding theoretical absolute sensibility curves. The curve that most nearly coincides with the experimental curve is adopted. For illustration consider the curves C and E, in Fig. 3. First divide the selenium into four imaginary layers, supposing that the light acts as though it penetrated uniformly to the bottom of the first layer. This is equivalent to saying that in the selenium there are four equal parallel conductors, all of which are affected alike by temperature and only one of which is altered by light. The initial conductivity is 15.8. Since curve E is taken from temperature variations it shows that when the conductivity of all the selenium and consequently that of the top layer is doubled, that the change of conductivity by the standard light is 2.75 instead of 4.2 as it was at the start. The conductivity of each of the four layers is 3.95. If the top

[1] See paper by Pfund, PHYS. REV., XXVIII., p. 324, 1909, also paper by Stebbins in Astrophys. Journal, XXVII., p. 183, 1908, on the color sensibility of selenium, in which he shows that for the Giltay cell there are two maxima instead of one as in the Rulmar cell or the cell used by Pfund.

layer is doubled by the variable light instead of by heat, the three remaining layers will be unchanged and the total conductivity will be

$$C = 3.95 + 3.95 + 3.95 + 2 \times 3.95 = 19.75,$$

and the change of conductivity by the standard light will obviously be $\Delta C = 2.75$. This point is indicated by the cross to the right of curve C. Further if the conductivity of all the layers is trebled, making a total of 57.4, the sensibility by the standard light is shown on curve E to be 2.17, and if the top layer is trebled by light, the total conductivity before exposure to the standard light is

$$C = 3.95 + 3.95 + 3.95 + 3 \times 3.95 = 23.70.$$

By the standard light this value is increased by the amount $\Delta C = 2.17$. This point is also shown to the right of curve C. And so on as many points as desired can be obtained for the theoretical curve when the light penetrates one fourth the depth of the conducting selenium.

By the same identical method theoretical curves for the absolute sensibility when the initial conductivity is varied by light can be obtained for any number of layers of selenium. The crosses to the left of curve C mark out such a theoretical curve when 12 layers are imagined, and those crosses that fall on curve C are those that obtain if it is supposed that there are 8 layers of selenium and that the effect of light penetrates to the bottom of the first layer. The conclusion here is that the effective penetration of red light is about one eighth of the total depth of the conducting selenium. Curves D and E when taken together show within the limits of experimental error that the red light penetrated one eighth the depth of the selenium when the initial conductivity is about double what it was at 21.5° C. The importance of this result, that the penetration is almost if not entirely independent of the conductivity, will be considered in the discussion.

The penetration by the blue light is the same as that by the red light. The crosses following curve A in Fig. 4 are obtained from curve B by supposing eight layers of selenium. These results are reliable probably within about ten per cent. It is worth comparing the sensibility curve for red light with the one for blue light. Curve E shows that when the conductivity is doubled that the sensibility is decreased 48 per cent., while curve B shows for doubling a decrease of 42 per cent. Just what the significance of this difference may be is not certain, but most probably it arises from experimental errors.

It will be shown in the succeeding paragraphs that all of the selenium in the Giltay cell is conducting and light-sensitive. The total depth of the selenium was estimated as previously stated to be 0.11 mm. One

eighth of this 0.014 mm. This result may look surprisingly large, but I believe that any discrepancies that may arise because of the inexact identity of heat and light action, are in favor of giving a larger result rather than a smaller one. The reader may think this conclusion is obvious, but because of the complexity of temperature action it is very difficult to prove.

THE EFFECT OF REMOVING THE SURFACE OF THE SELENIUM.

The result for the effective penetration, viz., .014 mm., that was stated in the last paragraph depended on the uniform structure of the selenium from top to bottom. It was to obtain information on this point that the surface of the selenium was filed away, and the conductivity and light-sensitiveness of the remaining portion was tested.

The first test was very crude. I took a piece of an old Giltay cell and by the use of a fine Swiss file, I carefully removed the selenium from the wires. It was noted that the cell was conducting until all the selenium was taken off, and that the selenium was light-sensitive even at the very bottom. The second test was a more careful investigation into the effects of filing. This time the selenium between eight parallel wires was considered. The total amount of the selenium was estimated at .06 gm. The conductivity in the dark was 87 mm. After filing away a small amount of selenium from all over the surface, I was greatly surprised to find that instead of the conductivity decreasing because of the slightly smaller cross sectional area, that it had actually increased about five fold. After 24 hours it still showed most if not all of this increased conductivity. It seemed that the filing had changed the properties of the selenium in such a manner as to increase its specific conductivity. After further removing what was estimated to be fully one half of the selenium, the conductivity fell to 170 mm. in the dark, which was however twice larger than what it was before any selenium was filed away. When 20 cm. from a 4 c.p. lamp the conductivity increased to somewhat more than 500 mm.

The third time the selenium was filed gave a conductivity of 90 mm. in the dark and more than 500 mm. in the light. By the fourth filing about 0.02 gm. of selenium was removed, and as far as the eye could detect there was almost no selenium left. However the conductivity was more than 43 mm. in the dark and more than 500 in the light. After 24 hours the conductivity in the dark fell to 20 mm. and when left for 20 seconds one cm. from a 16 c.p. lamp the conductivity increased sixty-six times. The maximum amount of selenium that could have been left was not more than one tenth of what was originally on the

part of the cell considered. These experiments indicate the following facts:

1. That filing changes the properties of the selenium so as to increase its conductivity, and that this at first lowered the relative sensibility to light.

2. By continued filing the relative sensibility, *i. e.*, the ratio of the conductivity in the light to that in the dark, increases.

3. All the selenium on the Giltay cell is conducting, and light-sensitive.

4. That further experiments must be carried on by carefully weighing the selenium removed by each filing in order to determine whether the filing produces a surface action or whether it is more deep seated.

The results that have just been stated were checked with a third sample of the cell, by filing away the selenium in three instalments. The following Table II. gives the results of the observations. In these the light intensity was kept quite constant in the comparative observations, although its value was not determined.

TABLE II.

Time of Observation.	Dec. 16, 10:00 A. M.	12:05 P. M.	12:24.	1:25.	10:30.	Dec. 17.	Dec. 18.
Conductivity in dark.....	4.2	9.6	10.	7.6	3	4	0.7
Conductivity with faint light.....	62.	100.	90.	75.	90.		
By intense illumination.....	85.	135.	118.	98.	130.	135.	20.
Comments.....		Some selenium filed off of entire surface.	Probably half of the selenium removed.	After resting since 12:30			After filing away a least $\frac{9}{10}$ of selenium.

If it is a fact, as the table indicates, that the conductivity did not change by separate filings very much after the first filing until nearly all the selenium was removed, then it is certain that the filing produces essentially a surface action.

Just twelve days after I had made the second set of observations just recorded, I received a letter from Mr. J. W. Giltay in which he described an experiment of the same nature as my filing experiment and which showed essentially the same result. A cell of 190,000 ohms resistance and sensibility 22 to 1 was exposed to a sand blast. Instead of the resistance increasing as he expected because of the removal of some of the selenium, it decreased to 70,000 ohms, and the sensibility became

only 8 to 1. After 15 days the resistance increased to 140,000 ohms and the sensibility to 25 to 1. The temperature was not read, but the resistance and sensibility of a second cell, which was treated like the first in all ways except that it was not subjected to the sand blast, indicated that at least a part of the apparent recovery during the 15 days was due to temperature change. Mr. Giltay states that this experiment seems to prove that the dark resistance was lowered by the sand blast, and also that the sensitiveness was lowered the same as by heating a cell. He attributes the effect to a possible action of the blast of a nature to alter the crystalline structure of the selenium.

THE DISCUSSION OF RESULTS.

It is perhaps safe to place as much confidence in the comparative determinations with different wave-lengths and with the selenium at different temperatures as is placed in the value of the absolute penetration. Whatever error may accrue in the determination of the absolute effective penetration because of the dissimilarity of heat and light action, would obviously be very much reduced in any comparative measurements by the same method. Therefore it is worth while to inquire into the significance of the comparative results.

The penetration by either red or blue light is practically the same. This conclusion would hardly be altered even if we regarded the difference in the falling off of the sensibility by red and blue light as due to experimental errors. If the curve E were reduced and substituted for curve B, the theoretical conductivity-sensibility curves for light would lie about as much to the right of the experimental curve as they now lie to the left of it.

It is generally expected that the penetration should increase with the increased wave-length. Pfund[1] showed for a thin film of a certain metallic variety of selenium that the absorption for light of $600\mu\mu$ was more than twice what it was for $700\mu\mu$. But we can not compare our result with his because the selenium used by him was a different variety from that found in the Giltay cell. Further the meaning of effective depth of penetration is not the same as maximum depth of penetration. It is quite possible that the effect of light goes much deeper than does the light itself. This would happen if there were any interconnected mechanisms reaching from the surface to the effective depth of penetration. Light would disturb one part and the disturbance would be felt equally throughout the region. Or the mechanism reached by light might extend throughout the selenium, in which case the disturbance would be greatest

[1] Paper already referred too.

at the surface and would diminish with increased depth, so that the effect would be the same as a uniform disturbance extending 0.014 mm. into the selenium. A single crystal in the selenium might include the mechanism, or the mechanism might be included in several crystals. It is perhaps useless to speculate further on the possible mechanism that would permit the effect of the light to penetrate deeper than the light itself. But if the view is correct then we should rather expect any agency that acts on the surface of the selenium to effect the selenium to about the same depth. Thus red light or blue light should effect the selenium to the same depth providing the light itself does not reach into the effected layer but relatively a short distance. This is probably the most reasonable explanation of the matter. If light should really have an average penetration equal to one eighth of the selenium thickness, then one might expect a small fraction of the light to penetrate entirely through the selenium. This was tried, roughly, however, with a negative result.

The results further show that the effective penetration does not vary with the conductivity. Supposing the conductivity to depend on the number of free electrons, then the absorption should vary with the conductivity, providing that the absorption is due to the free electrons as in the case of metals. We can at least say that there is no evidence against the view that the absorption in light-sensitive selenium takes place mostly in the non-conducting, *i. e.*, *A* and *C*, components, and not by the free electrons. I have previously shown that the amounts of the *A* and *C* components are not much altered relatively in the Giltay cell by illumination, while the relative alteration in the amount of the *B* component is very great. Thus we should expect that the penetration should not vary with the conductivity.

The fact that the effective penetration is only one eighth of the thickness of the selenium, will make a difference in the rates of interchange that were found necessary to explain the changes taking place in the Giltay cell,[1] and should therefore make it easier to explain the significance of the rates of change in terms of a few fundamental laws. Particularly the direct rate α_1 should be altered. If I find that making allowance for the incomplete penetration of selenium by light leads to conclusions of importance, I shall hope to get the results in shape for publication.

It seems worth while to investigate further the effect of filing the selenium surface. If the cell does not recover from the filing, it will add evidence on at least two important questions of theory. It will show that the two interchanges that theory has recently shown to exist between the *A* and *B* components and the *B* and *C* components are not

[1] See paper already referred to.

perfectly independent but are rigidly limited perhaps to interactions within given small boundaries, may be crystal boundaries. In addition if a simple mechanical operation such as filing can permanently alter the equilibrium rates in the dark without any chemical action, then it is safe to say that forces within the atoms themselves can maintain different permanent equilibrium rates. These conclusions are far reaching and will be discussed after more careful investigations.

SUMMARY.

1. The effective depth of penetration of the selenium in the Giltay cell by light is about one eighth of the thickness of the selenium.

2. The entire amount of the selenium on the Giltay cell is conducting and light-sensitive.

3. Therefore the effective depth of penetration is about 0.014 mm.

4. The effective depth may be very much greater than the greatest depth reached by the light.

5. The effect of filing or sand blasting the selenium surface is to increase the conductivity. The nature of the action is important and should be investigated further.

6. Knowing the depth of penetration, we can now solve for new rates of change which will be slightly different from those recorded previously, and their significance should be more apparent.

I wish to thank Mr. Ernest Dieterich for so ably assisting me in much of the experimental work and for his kind interest in the problem.

THE PHYSICAL LABORATORY,
THE UNIVERSITY OF IOWA.

RAYS OF POSITIVE ELECTRICITY FROM THE WEHNELT CATHODE.

By Chas. T. Knipp.

IN the December[1] number of the Philosophical Magazine, there appeared a preliminary note on "Rays of Positive Electricity from the Wehnelt Cathode." I wish now to supplement that note by a more extended description of the method and apparatus, and also by the inclusion of additional data that were collected last August while the apparatus was still set up at the Cavendish Laboratory.

As suggested in the paper referred to, the photographic method,[2] in which the plate was put inside of the vacuum tube, was employed. The fact that these carriers must be accelerated necessarily complicates the form of the apparatus.

The first requisite is that the path be made the shortest possible, consistent with ease of manipulation, if clearly defined photographs are to result. Again if large plates are to be used on which several exposures may be made, the lateral dimensions must be increased. As a result, then, the vital part of the apparatus assumed very unusual dimensions—small in the direction in which the rays travel, but large in directions at right angles to this, *i. e.*, large in diameter. This general form of the apparatus proved to have distinct advantages, as will be seen presently.

The apparatus as finally constructed is shown in Fig. 1. The containing vessel MN was a glass cylinder 35 cm. long by 10 cm. in diameter, made from an ordinary gas jar. The ends were each ground plane on emery cloth, and closed by a quarter inch plate pp, of plate glass. These were fastened to the cylinder by soft wax, sw (beeswax and resin half and half). To aid in affixing and removing the plates I arranged a circulating hot water system, designated by hw in the figure. The anode A, and the winch w, for turning the photographic plate, were brought in through the left end plate. The tubes carrying these were baked on to the end plates with Bank of England sealing wax. For further connections three openings were made through the side of the containing vessel MN, as shown in the figure. Through the upper left hand opening were brought the leading in wires for heating the cathode. The manner of supporting

[1] C. T. Knipp, Phil. Mag., Vol. 23, December, 1911.

[2] J. J. Thomson, Phil. Mag., Vol. 20, October, 1910.

these so as to make the position of the cathode adjustable is clearly shown. Through the lower opening of the large vessel connections were made to the electric field and to the accelerating condenser. The iron bob B, operating the shutter s, also hung in this tube. The system included two cocoanut charcoal bulbs, not shown in the figure. It may be well to

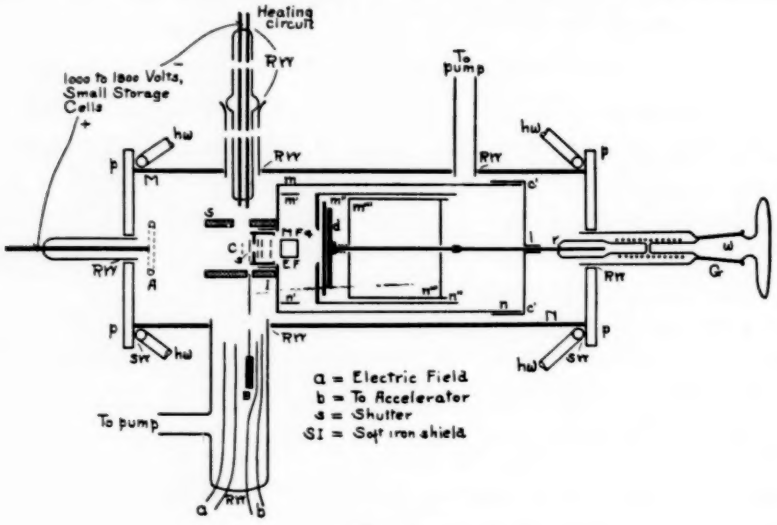

Fig. 1.

remark that all these joints were sealed with red wax designated by RW. Greater stability was secured by blowing an enlargement in the various tubes at the point where the wax was applied. These enlargements are not shown.

The apparatus proper was placed within the containing vessel MN. It consisted of a brass cylinder mn, closed by a brass disc at its forward (left) end, and a cap $c'c'$, at its rear end. An opening 3.5 cm. in diameter was made, off center, through the disc (see Fig. 4). In front of this opening the "objective" of the system was held by means of a slitted collar soldered to the disc.

Next to the end disc, and within, was placed a brass ring $m'n'$ telescoping the tube mn and carrying the iron magnetic field extensions, and also the electric field plates. These are designated by MF and EF. The tube mn was 21 cm. long, while the plateholder $m''n''$ was made 11 cm. long, thus giving ample room in which to vary the distance that the carriers travelled before striking the photographic plate. The opening in the front end of the plateholder was off center to correspond with the position of the objective. The plan was to make a number of exposures on the same plate by mounting it free to rotate about the axis

of the plateholder. The manner in which this was done is shown in Fig. 1. The photographic plate was fastened to the brass disc *d* at three points by means of the half and half wax, and cut circular. This disc carrying the plate was fastened by a swivel joint to the end of the rod *dr*, which in turn was supported, and free to turn, in the cap $m'''n'''$ of the plateholder. This cap telescoped into the plateholder $m''n''$. A spring at *d* held the plate against the opening. The other end of the rod *dr* was squared and fit loosely into a glass rod which in turn connected through a flexible spring joint to the winch *w*. By this arrangement the photographic plate could be turned at will either forward or backward. The apparatus was made perfectly light tight. The position of the cathode is shown at *c*. To guard against stray magnetic fields the objective and cathode were protected by the soft iron shield *SI*.

In Fig. 2 is given a dimensional sketch of the parts of the apparatus in the region lying between the cathode and the photographic plate. The over all dimension was 3.57 cm. The distance that the carriers travelled in going from the opening in the cathode to the first plate of the accelerating condenser was .82 cm. The plates of the accelerating condenser were .704 cm. apart, while the distance that the carriers travelled after emerging from the accelerator and before striking the photographic plate was 2.03 cm. This was the minimum distance for the apparatus as I then constructed it. Other dimensions are also given.

In Fig. 3 is given in detail the construction of the objective. It

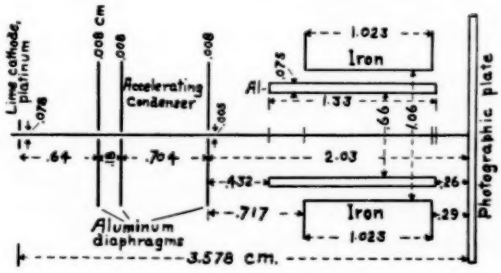

Fig. 2.

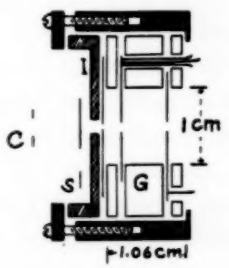

Fig. 3.

consisted of the outer case, made of brass (shaded dark in the figure), the heavy iron disc *I* to serve as a magnetic screen, and the three glass washers *G*, with central openings 1 cm. in diameter. These washers gave the proper spacing between the aluminum diaphragms. Additional holes *t* through two of the washers allowed contact to be made with the two plates of the accelerating condenser. The position of the cathode is shown, and *s* represents the shutter. Three aluminum diaphragms were used. The object of the third, the one towards the

cathode, was to sharpen the beam emerging from the system. The opening through each diaphragm was about .005 cm. in diameter. I experienced great difficulty in lining up the diaphragms. After numerous attempts the following plan was adopted and left nothing to be desired. The objective, with the various washers and diaphragms threaded on a fine phosphor bronze wire, was slipped into a closely fitting brass tube whose ends each were covered with a metal disc pierced in its center by a hole but little larger in diameter than the bronze wire. The wire was passed through these holes and one end was soldered to a support while the other was wound around a friction pin. A spring was included to prevent breaking the wire. A portion of the tube near the end was cut away, which together with openings through the disc, gave free access for tightening the three set screws in the objective after once the phosphor bronze wire was drawn taut.

The lime cathode was heated by induction, using the 110-volt lighting circuit. This method proved to be quite constant. The secondary of the transformer was hung loosely in position. The lime on the cathode was prepared by applying to it, while fairly hot, a minute quantity, evenly distributed all around the opening, of Bank of England wax.[1]

In Fig. 4 is given a section through the electromagnet viewed from the position of the photographic plate. The position of the objective and the leads b are also shown. MN is the glass containing vessel, mn the first brass tube (see Fig. 1), and $m'n'$ the brass collar which carried the iron pole extensions and also the electric field plates. These extensions were soldered to the brass collar. Other details are plainly shown in the figure.

Extra precautions were taken to screen the cathode and the accelerating condenser from stray magnetic fields. The soft iron screen around the cathode and the iron disc were quite effective. For the strongest fields used—1,800 gausses—the cathode beam suffered but a few millimeters deflection at the point where it emerged from the end of the cylindrical iron screen.

The plateholder held a circular plate 7.5 cm. in diameter, and by its manner of mounting at least four exposures were possible without overlapping. The circular form of the plate, and position of photographs, are shown in the half full sized reproduction given in Plate I., Fig. 8, on which three exposures were made. A precaution of great importance was to mark the center of the plate and thus locate the x-axis for the purpose of measuring the photographs. To do this the opening in the plateholder on the side toward the center was notched and with a sharp

[1] Suggested to me by E. Everett, of the Cavendish Laboratory.

lead pencil point placed in the V, I described a circle (by whirling the plate) whose center was afterwards easily determined. Obviously lines drawn from the undeflected center to this center gave the x-axis.

To measure the photographs I found it convenient to improvise an instrument consisting essentially of two micrometer screws mounted on a metal frame so as to move a stylus in two directions at right angles to each other. The arrangement of the various parts is shown in Fig.

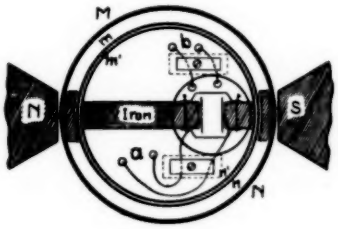

Fig. 4.

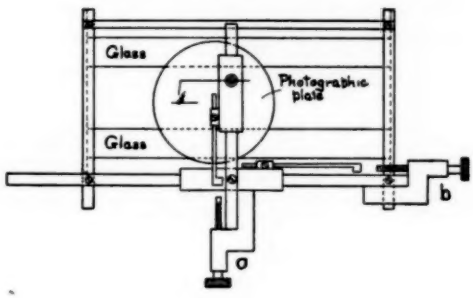

Fig. 5.

5. Two glass strips clamped in position across the bottom served to hold the plate in position. The latter was attached by a little universal wax. In mounting the plate in this "ordinator," it is only necessary to make sure that the line on the plate passing through the photograph to be measured is parallel to one of the slide ways of the instrument. This is readily done by moving the stylus back and forth along the horizontal way, and at the same time pressing the plate, held by the soft wax, firmly into position. I found that, for myself, more reliable measurements can be made with such an instrument and the unaided eye, than by the use of a microscope, or by photographic enlargement, or by projection on a screen.

All of the photographs discussed in the article previously referred to, show two, and on several plates, three and four lines. These varied greatly in sharpness and intensity from plate to plate. Two types of curves were obtained. First, those that were straight lines and passed out from the origin, and second, parabolas that had their heads on the same straight line. However, in the case of the two later plates, there appeared on each photograph but one prominent line. These plates will be taken up presently. In addition to these I have selected for reproduction here photographic plates 20 and 26 from my former paper. Photograph 20 is reproduced, both half full sized and enlarged, in Plate I., Figs. 6 and 7, respectively. In many respects this was one of my most successful exposures. As was pointed out in my former paper, the

measurements on this photograph showed that the curves are most likely due to the hydrogen atom with one charge, the hydrogen molecule with one charge, the atom of carbon with two charges, the atom of oxygen with one charge, and also other substances of greater atomic weights.

In the paper referred to I gave an enlarged reproduction of, and also an extended table exhibiting measurements made on photographic plate 26. The reproduction, however, did not show the lines as well as was expected. The importance of this plate warrants its reproduction half full size in Plate I., Fig. 8. As will be noticed three exposures were made on it. The conditions of exposure were as follows:

TABLE I.

Plate and Exposure.	Pressure in Mm. Hg.	H in Amperes.	$X \times d \times 10^8$	Accel. Field in Volts.	Exposure in Min.	C_1	C_2
26*a*	.0068	8.83	171	1,548	45	1.63	.55
26*b*	.0072	8.61	168	1,548	45	1.64	.56
26*c*	.0062	1.00	167	1,540	30	—	—

Exposures *a* and *b* admitted of easy measurements, while exposure *c* with the conditions practically the same, except that there was only 1 ampere flowing through the electromagnet instead of over 8, came out in an unexpected manner. The direction of this field was the same as that in *a* and *b*. By reference to the photograph we see that the positive rays in *a* and *b* are deflected to the right and up. Now exposure *a* also shows a rather faint deflection to the right and *down*. Exposure *c* shows a diffused line deflected to the right and up. It is puzzling why the line should be diffused. Again this exposure shows a number of sharply marked lines both to the right and left and all *down*. Those to the left and down may possibly be due to carriers atomic in size and having negative charges, though this is hardly probable since they are deflected at an entirely different angle than the diffused line due to positive rays in the first quadrant. Those to the right and down at present seem to defy a rational explanation. The main ray of this beam starts at a point a little below the x-axis and at some distance to the right of the origin. There are a number of circumstances that might conspire to produce this seemingly erratic exposure, such as residual magnetism, or a reversed magnetic field. However, since this is the only plate that shows it, further speculation as to its explanation must be postponed until additional data are collected. Plate 26, as a whole, is interesting in that it is a reproduction of a typical photographic plate showing the relative positions and orientations of the various exposures.

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Fig. 6.
Half full size.

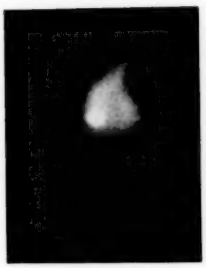

Fig. 7.

Fig. 8.
Half full size.

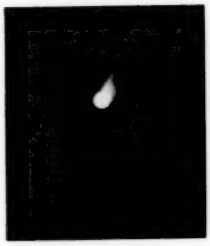

Fig. 10.

Fig. 9.
Half full size.

Fig. 11.

CHAS. T. KNIPP.

PLATE I.

The limited time at my disposal last August prevented improvements being made or work with gases other than residual air. I therefore decided to try for more perfect photographs with the apparatus as it was. My first attempt was to drive the hydrogen lines off the plate and thus bring into prominence, if possible, lines due to the heavier elements. To do this I increased the magnetic field by several amperes, used a stronger accelerating field, and also a higher discharge potential than in any of the previously taken photographs. The electric field, however, was not increased. Three exposures of 15 minutes each were made. These proved too short. The conditions were changed slightly and another, plate 33, was exposed on the following day for a longer time. This was followed by a third exposure, plate 34, in which the time was made still longer. The conditions under which these two plates were exposed are given in Table II.

TABLE II.

Plate and Exposure.	Pressure in Mm. Hg.	H in Amperes.	$X \times d \times 10^8$	Accel. Field in Volts.	Exposure in Min.	Average Terminal Voltage.
33*a*	.0038	12.9	129	1,615	60	490
33*b*	.0045	12.3	128	1,585	60	790
34	.0041	12.3	122	1,651	125	1,060

Photographic plate 33 had two successful exposures on it, while on plate 34 there was but one exposure made. These photographs are reproduced in Plate I. Fig. 9 is a half full-sized reproduction of 33*a*, and Fig. 10 is the same enlarged. Fig. 11 is an enlarged reproduction of 34. Measurements made on these plates and the values calculated therefrom are given in Table III.

TABLE III.

Plate and Exposure.	Line.	x in Mm.	y in Mm.	C_1	C_2	v from Curve $\times 10^7$.	v Calc. $\times 10^7$.	v Slowed Down in %.	e/m $\times 10^4$	Elect. Atomic Wt.	Element.
33*a*	*a*	1.44	5.57	.92	.23	3.70	3.97	7.0	.49	2.04	H_2+
33*a*	a_1	1.44	3.50	.92	.23	2.23	2.47	7.0	.19	5.26	C++
33*b*	*a*	1.38	5.14	.96	.25	3.56	3.90	8.7	.48	2.08	H_2+
33*b*	a_1	1.38	3.19	.96	.25	2.21	2.42	8.7	.185	5.40	C++
34	*a*	1.25	4.96	.92	.245	3.65	3.98	8.3	.48	2.08	H_2+
34	a_1	1.25	3.12	.92	.245	2.29	2.55	10.0	.19	5.26	C++

All three exposures show but one line clearly. This is line a_1 given in the table, and, judging from its electric atomic weight, it must be due to the carbon atom with two charges (Plate I., Figs. 9, 10 and 11).

The negatives also show faint traces of another line located above the

extremity of the line a_1 just mentioned. I doubt very much whether the reproductions, either the half full-sized one or the enlargements, show this line. This is line *a* given in the table. It corresponds to the hydrogen molecule with one charge. Had a stronger magnetic field been applied this line too would have been blown off the plate.

These photographs also show a displacement of carriers of positive electricity having much smaller *y* values, and, furthermore, that the curves end on the same vertical line. As stated in my former paper this value of *x* represents the division line between the straight lines out from the origin and their parabolic continuations. The photographs, however, do not show these continuations. The definition in plate 34 is not as good as that in either 33*a* or *b*, though the former was exposed twice as long. It is difficult to keep the conditions constant over a period of two hours of continuous discharge.

Plate 34, however, brought out one thing that did not appear in the others, and that is that there are carriers of *negative* electricity atomic in size also present. This negative counterpart shows only very faintly on the plate and not at all in the reproduction. I was not able to make accurate settings on it.

Another interesting point is brought out in Table III. The velocity of the carriers was reduced about 10 per cent. by impact with the remaining molecules of gas in the discharge tube, in travelling the 2.03 cm. length of path between the emerging diaphragm and the photographic plate.

SUMMARY.

In this paper a detailed account is given of the apparatus used in studying the positive rays from the Wehnelt cathode.

Photograph 20 of my previous paper is included, both enlarged and half full sized.

Photographic plate 26, also of my previous paper, is here reproduced in its entirety half full sized. It shows in a striking manner that the phenomenon that we are dealing with is of a complex nature and easily disturbed by factors that must not be overlooked.

In addition to the above, reproductions of two new photographs are included, and the points brought out relative to these may be briefly stated thus:

1. For the conditions under which these photographs were taken (see Tables II. and III.) they show but one prominent line, and that seemingly corresponds to the carbon atom with two charges. This is in agreement with the data and the photographs discussed in my former paper. The line due to the hydrogen atom is blown completely off the plate, while

that due to the hydrogen molecule is seen as a faint trace (the head of the parabola) just above.

2. The last exposure made, photographic plate 34, after an exposure of over two hours shows a negative counterpart. This line, however, is too faint to admit of accurate measurement and identification.

Further investigation of the properties of these rays is in progress.

In conclusion I wish again to thank Professor Sir J. J. Thomson for making it possible for me to continue the work through the month of August, and for the services of his shop assistants who so kindly helped me in many ways.

LABORATORY OF PHYSICS,
UNIVERSITY OF ILLINOIS,
December 23, 1911.

NOTE ON THE MEASUREMENT OF THE PELTIER E.M.F.

BY HAROLD C. BARKER.

A RECENT article in this journal[1] includes the results of some measurements of the Peltier E.M.F. which I think fail to do justice to the method used. The frequent extreme disparity between the two compensation terms, which should be nearly alike, seems to require explanation. The method, in the cases referred to, was that devised by me in April, 1910, and published October, 1910.[2] At that time I gave the results of a series of ten measurements of the Peltier E.M.F. for nickel-copper, the mean being 6.75×10^{-3} volts at 28.7°. During July and August of the present year (1911) after further investigation of the method, and improvement in the mechanical arrangement of the apparatus, the following determinations were made. None of those made are omitted. The junctions were those previously used.

Working formula:

$$P = \frac{ai_a^2 + bi_b^2}{4ni}.$$

$n = 5$ (number of junctions).

ai_a^2	bi_b^2	i	P	Approx. Mean Temperature.
.1128	.0983	1.50	7.04×10^{-3}	30.0°
.1093	.1047	1.60	6.69	28.5
.1152	.1113	1.70	6.66	29.0
.1224	.1158	1.80	6.62	26.5
.1324	.1251	1.90	6.78	29.0
.1349	.1298	2.00	6.62	28.5
.1508	.1322	2.10	6.74	28.5
.1508	.1421	2.20	6.66	28.0
.1591	.1446	2.25	6.75	29.5
.1591	.1550	2.30	6.83	29.5
.1676	.1603	2.40	6.83	29.5
.1792	.1563	2.50	6.71	30.5

Mean of twelve results: $P = 6.74 \times 10^{-3}$ volts at 28.9°.

[1] Caswell, PHYS. REV., XXXIII., 5, November, 1911.

[2] Barker, PHYS. REV., XXXI., 4, October, 1910.

A second series, repeating eleven of the twelve values of i, resulted as follows:

ai_a^2	bi_b^2	i	P	Approx. Mean Temperature.
.1036	.0963	1.50	6.66×10^{-3}	28.0°
.1082	.1091	1.60	6.79	30.5
.1105	.1113	1.70	6.52	25.5
.1200	.1204	1.80	6.68	28.5
.1273	.1262	1.90	6.67	27.5
.1349	.1322	2.00	6.68	30.0
.1401	.1446	2.10	6.78	32.0
1454	.1485	2.20	6.68	28.0
.1563	.1576	2.30	6.82	30.0
.1676	.1603	2.40	6.83	30.0
.1763	.1684	2.50	6.89	30.0

Mean of eleven results: $P = 6.73 \times 10^{-3}$ volts at 29.1°.

There is no doubt still room for investigation, and certainly for extension, of the method. I have great confidence in its validity. I will be glad if others shall contribute to the development of the method, and I hope to do so myself, following ideas now fairly definite. Mr. F. W. Jordan[1] has done some highly interesting work along somewhat similar lines.

THE RANDAL MORGAN LABORATORY OF PHYSICS,
UNIVERSITY OF PENNSYLVANIA.

[1] Jordan, Phil. Mag., April, 1911.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

MINUTES OF THE SIXTY-FIRST MEETING.

A REGULAR meeting of the Physical Society was held in Fayerweather Hall, Columbia University, New York City, on Saturday, March 2, 1912, President W. F. Magie occupying the chair.

At the business meeting, which was held at the beginning of the afternoon session, the Society proceeded to vote upon the two amendments to the constitution which had been proposed at the preceding meeting and notification of which have been sent to all members by the secretary on January 23, 1912. Messrs. Gordon and Pegram being appointed tellers, the votes cast by mail and in person were counted and the amendments were declared adopted, the first by a vote of 118 to 9 and the second by a vote of 125 to 3.

As amended Articles IV. and V. read as follows, the changes introduced by the amendments being indicated by italics:

IV. The officers of the Society *and all those who have at any time held the office of President of the Society*, together with eight other members *to be elected in the manner specified in Art. V.*, shall constitute a Council, which, shall have general charge of the affairs of the Society.

V. The officers of the Society and *the other elected* members of the Council shall be elected by ballot at the Annual Meeting of each year. An official ballot shall be sent to each member at least one month prior to the Annual Meeting, and such ballots, if returned to the Secretary in envelopes bearing the names of the voters, shall be counted at the Annual Meeting. *At least two months before the Annual Meeting the Secretary shall send to each regular member of the Society a request for nominations, specifying what vacancies are to be filled. The names of all those who are nominated by not less than 20 members shall be printed on the official ballot.* The official ballot shall *also* contain a name proposed by the Council for each vacancy, with blank spaces in which the voter may substitute other names. A majority of all votes cast in person or by mail shall be necessary to election. In case of failure to secure a majority for any office, the members present at the Annual Meeting shall choose by ballot between the two having the highest number of votes. The term of office shall be one year for officers and four years for other elected members of the Council, and until their successors shall be elected. No member shall be elected as president more than two years in succession. No elected member

of the Council, having completed a term of four years, shall be re-elected until at least one year shall have intervened.

The secretary reported from the council a recommendation that Article IV. of the By-laws be amended by striking out the sentence reading "The meetings shall ordinarily be held in New York," and by inserting at the beginning of the article the words "At least." The proposed amendment was adopted by the meeting, so that Article IV. of the By-laws will now read as follows:

IV. At least four regular meetings shall be held each year, at such times and places as shall be ordered by the Council. One of these, to be called the Annual Meeting, shall be held on such day as the Council may decide upon between the 26th and the 31st of December inclusive.

It was also recommended by the council that Article VI. and Article IX. of the By-laws be repealed and this action was taken by the meeting.

On behalf of P. G. Nutting the secretary introduced a motion for the appointment of a committee of three to ascertain the sentiment of the members of the society in regard to desirable changes in the Constitution and By-laws, with a view to later revision. This motion was ruled out of order under Article VII. of the By-laws. On motion of Mr. Franklin it was then voted to request the council to take the proposition of Mr. Nutting under consideration.

On motion of Mr. Franklin it was voted to request the council to consider the advisability of having only one class of membership and of adopting a more liberal policy in regard to election to the Society.

On motion of Mr. Richardson it was voted to ask the council to consider the advisability of increasing the dues of regular members while leaving the dues of associate members unaltered.

The following papers were presented:

Measurements with a Moving Light Photometer. C. C. TROWBRIDGE.

The Positive and Negative Ionizations from Heated Salts. CHARLES SHEARD.

The Ions Emitted by Hot Salts. O. W. RICHARDSON.

Models to Illustrate the Stresses in a Twisted Cylinder. W. S. FRANKLIN.

On the Expansion of an Alternating Current E.M.F. in a Fourier's Series. GEORGE R. OLSHAUSEN.

Change of State. Discussion of a General Case. A. J. LOTKA.

The Solar Eclipse of April 28, 1911. (Illustrated.) L. A. BAUER.

The Electron Theory of Conductors. O. W. RICHARDSON.

A Method of Using the Photoelectric Cell in Photometry. E. L. NICHOLS and ERNEST MERRITT.

On the Free Vibrations of a Lecher System using a Lecher Oscillator, II. F. C. BLAKE and CHARLES SHEARD.

On the Effect of Close Electrostatic Coupling on the Free Period of a Lecher System. F. C. BLAKE and CHARLES SHEARD.

The Electron Theory of Phosphorescence. C. A. BUTMAN.

The Absorption Spectrum of Molybdenum Sulphide. A. TROWBRIDGE.

The Theoretical and Experimental Determination of Reflection Coefficients. J. G. TATE.

A New Radiation from Polonium. H. A. BUMSTEAD and A. G. MCGOUGAN.

The Effect of a Magnetic Field on the Photoelectric Discharge. A. W. HULL.

Magnetic Reactions produced by a Copper Disc Rotating between the Poles of a Magnet. W. G. CADY and F. G. BENEDICT.

International Candle-power Measurements. CLAYTON H. SHARP.

Variation of Electrical Resistance with Temperature. Oxides. A. A. SOMERVILLE.

ERNEST MERRITT,
Secretary.

A SENSITIVE BLACK-BODY-VACUUM THERMAL-JUNCTION AND A METHOD OF PRODUCING HIGH VACUA.[1]

BY A. H. PFUND.

THE metals used in the construction of thermal junctions were the well-known Bi alloys of Hutchins. In order to produce thin bars, 5–10 grs. of an alloy was melted in a small crucible and the molten mass was violently hurled "tangentially" at a large piece of plate glass lying upon a table. As a result of this procedure the metal was spun out into fine filaments some of which were entirely too fine to handle. Those actually used were about 0.15 mm. wide and about 0.01 mm. thick. After many failures the following very satisfactory method of soldering was evolved: two bits of filament, prepared from the two alloys, were laid end to end on a piece of glass under which a piece of white paper had been placed; next a very small piece of low melting-point solder was melted on a strip of glass (1 × 5 × 50 mm.). This bit of molten solder was covered with a little non-corrosive soldering wax whereupon the solder drew itself up into a tiny globule. The glass strip was then inverted and the molten globule was brought immediately over and in contact with the meeting point of the filaments. As soon as the globule had solidified, a condition which could be recognized by noting the instant at which the metal took on a whitish color, pressure was applied to the glass strip immediately over the globule by means of the point of a knife blade and thus the globule was flattened out into a very thin disc (about 1 mm. in diameter) in which the filaments were imbedded. In a similar manner, fine copper wires, previously tinned, were soldered to the free ends of the filaments, thus completing the junction.

After having blackened the little discs, the middle one was mounted at the center of a small spherical mirror which consisted of two hemispherical portions. These were prepared simply by forcing a steel bicycle bell (about 12 mm. in diameter) into a piece of ordinary solder by means of a vise. This procedure furnished a splendidly polished mirror which was ready for use after the sides had been trimmed and a diametral hole 2 mm. in diameter had been drilled through it.

The following data were obtained from a thermal junction which was only

[1] Abstract of a paper presented at the Washington meeting of the Physical Society, December 27–30, 1911.

about one half as sensitive as some which have been tested. Nevertheless these results will suffice to indicate what may be accomplished. It may further be stated that the vacuum in these experiments was produced by a method to be described shortly.

Dimensions of each filament 0.01 × 0.15 × 5.0 mm.

Diameter of central disc, 1 mm. Total resistance 5 ohms.

D'Arsonval galvanometer: 7 ohms resistance; working sensibility, 2×10^{-9} amp.

Radiation from a standard candle at 1 meter, passing through a rock salt plate 1 mm. thick gave rise to the following galvanometer deflections.

I. Junction in air without reflecting enclosure: deflection 16 mm.
II. Junction in air with reflecting enclosure: deflection 17 mm.
III. Junction in vacuum with reflecting enclosure: deflection 210 mm.

It is evident that the sensibility has been increased more than 13 times. Previous experiments showed that the evacuation alone produced only a 5–6 fold increase. It may at first sight appear surprising that the reflecting enclosure produced so slight an increase in sensibility when the junctions are in air and yet leads to a very great increase in conjunction with a vacuum. The reason for this state of affairs becomes evident when it is recalled that the convention losses of the heated junction are tremendously greater than the radiation losses, hence, as long as the junctions are surrounded by air, a reflecting enclosure can add but little to the sensibility.

Since Thomson galvanometers having a sensibility of 1×10^{-10} amperes are readily obtainable, it is permissible to make calculations on this basis and outline further work. When E. F. Nichols measured the total radiation from Jupiter, Vega and other planets and stars, he employed a radiometer with circular vanes 2 mm. in diameter, yielding a deflection of 724 mm. per meter-candle at a scale distance of 183 cm. Used in conjunction with a concave reflector 61 cm. in diameter, he obtained a deflection of less than 2 mm. from Jupiter, the most brilliant source studied. The preliminary measurements already cited would seem to indicate that the vacuum thermal junction used in conjunction with a Thomson galvanometer is many times more sensitive than Nichols' radiometer. In view of the fact that a concave reflector 76 cm. in diameter has been placed at our disposal, Dr. J. A. Anderson and I intend, shortly, to attack the problem of stellar radiations once more. A differential thermal couple as well as a Thomson galvanometer are being constructed in preparation for this work.

The method of producing moderately high vacua about to be described is based upon the well-known phenomenon of self-evacuation exhibited by vacuum tubes. The essentials of the apparatus appear in the diagram which has been drawn to scale. The upper electrode A is a cylinder of aluminium while the lower electrode C is a mass of cocoanut charcoal within which a platinum wire 15 mm. long is imbedded. It has been found essential to pulverize the charcoal and reheat to redness on a piece of sheet iron until luminous flames are no longer visible. The electrodes are connected to the secondary of a small

transformer T, whose primary is supplied with current under a potential difference of 110 volts (60 ~) and whose secondary yields 2,000 volts. At first the tube is evacuated by means of an air pump to 1 or 2 mm. of Hg pressure and a discharge sufficiently heavy to generate hydrocarbon vapors and to raise some of the charcoal particles to red heat is permitted to pass for several minutes. These gases are then thoroughly pumped out and the tube, after being permitted to cool down entirely, is flushed with air and is finally re-exhausted to the limit of the pump. Sufficient resistance is then introduced at R to send a weak discharge through the tube. An oscillating mirror shows this discharge to be unidirectional—the carbon formingt he anode. Experiments show that the absorption of gases takes place only while the discharge is passing and that the gases absorbed are retained. If, at the beginning of the discharge, the cathode dark-space around A was but 1–2 mm. it is found to have lengthened to 2 cm. or more in about 1 minute. Rather suddenly the discharge becomes feeble and but little further evacuation takes place. Next, the current through the primary is increased until a fairly vigorous discharge is again started and the same changes in the discharge are permitted to take place. This operation is repeated until, finally, the full 110 volts are on the primary. It is necessary to caution against sending too heavy a discharge through the tube at any time, for, under such conditions, gases are generated instead of being absorbed. In order to carry the evacuation further, a small Wehnelt cathode, connected to the battery B and key K_2, is inserted at W. Upon closing the keys K_1 and K_2 and heating this cathode to incandescence, a vigorous discharge is again started and gases are again absorbed. Starting with a dark space of 2 mm., the time required by such a bulb to exhaust itself as far as it will go is less than two minutes. Although no definite measurements as to the degree of evacuation attainable have been carried out, this much may be stated: the discharge from a large induction coil will jump over an alternative spark gap of 15 mm. rather than pass through the tube. To be sure, this method does not rival that of Dewar; nevertheless it offers a very simple means of obtaining a moderately high vacuum free from mercury vapor without the use of liquid air. The degree of evacuation is under perfect control and it seems that such a charcoal tube ought to find numerous applications—as, for example, to portable radiometers and vacuum thermal junctions. Further experiments are in progress.

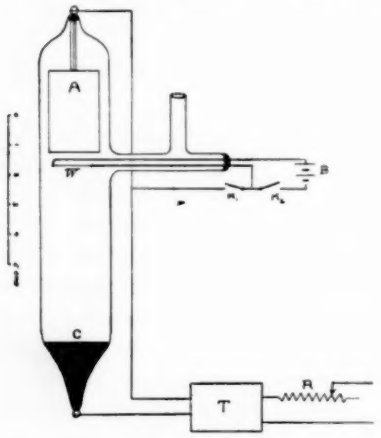

Fig. 1.

JOHNS HOPKINS UNIVERSITY,
December, 1911.

The Absorption of Gamma Rays of Radium by Air at Different Pressures.[1]

By Henry A. Erikson.

THE γ rays were passed through the aluminium windows of a heavy iron cylinder into which air was admitted at various pressures up to 200 atmospheres. The rays after passage through the cylinder entered a cylindrical ionization-chamber of 2 cm. diameter. The aluminium window between the compressed air and the ionization-chamber was 1 cm. thick and served as a screen for the β rays that came to it.

The absorption of aluminium was also obtained by using aluminium plates in the place of the compressed air.

The results of this investigation are represented by the equation:

$$D \text{ or } P = K(t - t_0),$$

where D and P are thickness and pressure respectively, K is a constant, t and t_0 the times required for a given deflection with and without the absorbing medium, due to the current in the ionization-chamber.

The relation between the intensity I and the thickness D or the pressure P of the absorbing medium is obtained by substituting in the above equation the values of t obtained from the relation $I = C/t$. This gives:

$$I = \frac{I_0}{1 + \left(\frac{I_0}{KC}\right) D} = \frac{I_0}{1 + \lambda D},$$

where λ is a constant. The constancy of λ was tested experimentally by using rays of different intensities.

Sir J. J. Thomson has shown[2] from theoretical considerations when only scattering of the γ rays takes place that

$$I = \frac{I_0}{1 + \frac{1}{2}hD},$$

where h is the coefficient of scattering.

The agreement of this with the experimental results given above suggests that when γ rays pass through matter the intensity of the rays is diminished mainly by scattering.

Physical Laboratory,
University of Minnesota.

The Stark-Doppler Effect for Hydrogen Canal Rays in Air.[1]

By Gordon S. Fulcher.

IT has been found that light is produced by the collision of canal rays with gas molecules.[3] An attempt was made to explain the details of the Stark-Doppler effect, assuming the molecular collisions obeyed the laws of ordinary,

[1] Abstract of a paper presented at the Washington meeting of the Physical Society, December 27–30, 1911.

[2] Cond. through Gases, p. 407.

[3] Fulcher, Astrophysical Journal, 33, 28, 1911.

perfectly elastic impact. This was found to involve other assumptions which seemed improbable. The fact that an α particle can ionize over 10^5 molecules of air before being stopped, suggested that the assumption of elastic collision was erroneous. An experiment has been arranged to test this.

In the apparatus used, hydrogen canal rays, passing through a small hole in the cathode, shot into a fine capillary through which air was streaming continuously. The capillary was arranged so as to be at the focus of the collimating lens of a two-prism spectrograph. It was also inclined at an angle of 45° to the axis of the collimator so that any sources of light in motion down the capillary would have a velocity component in the line of sight. The capillary thus acted as the slit of the spectrograph and enabled the spectrum of the light produced in it by the collisions of canal rays, gas molecules, and electrons to be photographed.

The hydrogen series lines, $\lambda\lambda$ 4861 and 4341, showed the Doppler effect clearly; but no trace of the corresponding unshifted lines, which are usually also present, was visible. The nitrogen bands were unshifted. This seems to prove that the hydrogen canal rays retain a considerable part of their momentum after the collisions with air molecules which cause the emission of the light; that is, the collisions are not elastic but more like those occurring in the case of α particles. Since the hydrogen canal rays are much slower, the mean deflection produced per molecule ionized is probably much greater than in the case of the α rays with which Geiger experimented,[2] but not nearly as great as if the collisions were elastic.

WISCONSIN UNIVERSITY.

TEMPERATURE INFLUENCE UPON THE REFRACTION OF QUARTZ, BORO-SILICATE CROWN GLASS, AND DENSE FLINT GLASS, FROM 100° C. TO −190° C.[1]

BY F. A. MOLBY.

A FORM of apparatus for low temperature work upon linear expansion of specimens about one centimeter in length, and the study of the optical thickness of solid plates by the method of interference, was described. Curves showing the effect of low temperature upon the refractive index of quartz (ordinary ray), and of flint glass, were discussed; four wave lengths of light 435.9$\mu\mu$, 476.0$\mu\mu$, 546.1$\mu\mu$ and 643.8$\mu\mu$ had been used in obtaining the data for the curves, temperatures ranging from 100° to − 188° C. Results for $\delta N/\delta T$ in quartz between room and steam temperatures agree well with those obtained by Fizeau, Reed, Pulfrich and others. The value of $\delta N/\delta T$ (usually designated as simply δN) is found to diminish by a measurably small amount as the quartz is cooled to lower temperatures. With dense flint glass the value of $\delta N/\delta T$ diminishes very greatly at the lower temperatures. With boro-silicate crown glass $\delta N/\delta T$ is small but measurably positive for a mean value between 20° and 100° C.; it becomes negative for a mean value between 20° and − 188°, and is much greater in magnitude at the lower temperatures.

[1] Abstract of a paper presented at the Washington meeting of the Physical Society, December 27–30, 1911.

[2] Proceedings Royal Society, 83–A, 492–504, 1910.

Slit-Width Corrections in the Photometry of Black Body Spectra.[1]

By Edward P. Hyde.

SOME years ago Runge evaluated the correction which must be applied to the observed energy curve of a radiant source, as determined with the infra-red spectrometer and linear bolometer or thermopyle, in order to obtain the true curve of energy distribution. This correction is necessitated by the impurity of the spectrum arising from the finite widths of the bolometer strip and the collimator slit, and the magnitude of the correction depends on the magnitude of these widths, on the form of the energy curve and on the dispersion curve of the prism.

Until recently no attention was paid to the necessity of slit-width corrections in spectro-photometric comparisons. About two years ago Nichols and Merritt published a formula for correcting the observed energy curves of band spectra in the visible region which undergo marked deformation when the correction for impurity of spectrum is applied. At about the same time the author published a formula differing but very slightly from that of Nichols and Merritt, but which had been developed for correcting energy curves of the black body type in the visible spectrum, obtained by spectro-photometric comparison of two sources using the *substitution method*. It was desired to find, for example, to what extent the visible energy curve of a black body at 2500° abs., determined by spectro-photometric comparison with a black body at 1500° abs., would differ from the true curve at 2500° abs.

In the present paper various numerical results for the case of a Lummer-Brodhun spectrophotometer are given. Moreover, computations are made showing to what extent errors will arise in determining the temperature of a black body at some unknown temperature, say *about* 2500° abs., from spectro-photometric comparison with a black body at some different known temperature, say 1500° abs. The magnitude of the correction depends on the absolute and relative sizes of the collimator and ocular slits, on the dispersion of the prism, and on the difference between the luminosity curves of the two sources. If a represents the width of the ocular slit and b that of the collimator slit, then for a given value of $a + b$ the correction is least when $a/b = 1$ and increases as the ratio differs from unity.

If we let δ represent the relative correction to the emission at λ_1 compared with that at λ_2 when the energy distribution in the visible spectrum of a black body at 2500° abs. is compared spectro-photometrically with that of a black body at 1500° abs., and if we let ΔT be the correction to the temperature at about 2500° abs. as obtained by computation from the spectro-photometric ratios, then the following approximate data show the magnitude of the correction for a few special cases:

$\lambda_1 = 0.51\mu$	$\lambda_2 = 0.625\mu$
$a = 0.4$ mm.	$b = 0.4$ mm. (approximately)
$\delta = +1.5\%$	$\Delta T = +10°$

[1] Abstract of a paper presented at the Washington meeting of the Physical Society, Dec. 27–30, 1911.

$\lambda_1 = 0.51\mu$	$\lambda_2 = 0.625\mu$
$a = 0.8$ mm.	$b = 0.8$ mm. (approx.)
$\delta = +6\%$	$\Delta T = +40°$
$\lambda_1 = 0.50\mu$	$\lambda_2 = 0.67\mu$
$a = 0.4$ mm.	$b = 0.4$ mm. (approx.)
$\delta = +3\%$	$\Delta T = +25°$
$\lambda_1 = 0.50\mu$	$\lambda_2 = 0.67\mu$
$a = 0.8$ mm.	$b = 0.8$ mm. (approx.)
$\delta = +12\%$	$\Delta T = +100°$

In every case the correction is in the direction to increase the emission in the short wave-lengths at the higher temperature, and hence to increase the observed value of the higher temperature in order to get the true temperature. Direct experimental confirmation in certain tested cases has been found.

PHYSICAL LABORATORY,
NATIONAL ELECTRIC LAMP ASSOCIATION.

A NEW RADIATION FROM POLONIUM.[1]

BY H. A. BUMSTEAD AND A. G. MCGOUGAN.

IT has been recently shown by one of the writers that the secondary δ-radiation, emitted by a metal when struck by α-rays, varies with the speed of the α-particles in a manner entirely similar to the variation in the ionization of a gas with the speed of the α-rays producing it.[2]

In these experiments the polonium preparation which served as the source of α-rays was enclosed, with the metal plate, in a charcoal vacuum. The speed (or range) of the α-particles was varied by interposing various thicknesses of aluminium foil between the polonium and the plate. The apparatus was arranged so that this could be done from the outside of the evacuated chamber.

In the continuation of this investigation, evidence has been obtained of a hitherto unrecognized radiation from polonium. As the thickness of the aluminium, through which the α-rays must pass, is gradually diminished, the number of δ-particles escaping from the plate varies in an entirely regular manner (like that shown by a Bragg ionization curve) down to the thinnest obtainable aluminium leaf (thickness 0.68×10^{-4} cm., equivalent in its effect on the α-rays to 1.2 mm. of air). When, however, the polonium is entirely uncovered, the loss of electrons by the metal plate is markedly increased. This effect (which amounts to 109 per cent. of the effect produced by the α-rays) has been shown to be due to a very "soft" radiation which is stopped by one layer of thin aluminium leaf. The greater part of this radiation appears

[1] Abstract of a paper presented at the New York meeting of the Physical Society, March 2, 1912.

[2] Bumstead, Am. Jour. Sci., XXXII., p. 403, 1911; Phil. Mag., XXII., p. 907, 1911.

to consist of electrons projected from the polonium with various velocities corresponding to a fall of potential of from 160 to 500 volts. This is much faster than δ-rays and much slower than ordinary β-rays. A smaller portion of the new radiation is not appreciably cut down by an opposing potential of 880 volts; it is possible that this part of the effect is due to recoil atoms. Wertenstein[1] has observed that, in the case of RaC, the recoil atoms produce an ionizing effect in air.

It is of course uncertain whether the new radiation is due to polonium itself or to some other radioactive substance associated with it in the preparation used. As time goes on, and the polonium decays it will be easy to determine this point; if the "soft" radiation falls off at the same rate as the α-radiation, it must be due either to the polonium or to some product of short life which follows it.

An easily absorbed radiation of this character can readily escape detection in ordinary ionization measurements unless they are carried out at very low pressures. It is not impossible that many radioactive substances which have hitherto been regarded as "rayless" may give out radiation of this type, or it may prove that rays of this character always accompany the emission of α-rays.

Change of State. Discussion of a General Case.[2]

By A. J. Lotka.

WE are all familiar with the treatment of discontinuous systems in the physics of change of state and in physical chemistry.

Very much less attention has been paid by physicists to the discontinuous systems presented to us in nature by aggregates of biological species. Evidently we may seek to investigate the time-changes in the distribution of matter among the several species, just as the physical chemist investigates the time-change in the distribution of matter among the several compounds and phases of which a chemical system is composed.

The purpose of this paper is to present a general method sufficiently broad to be applicable not only to a large class of cases of interest to the physical chemist (including for example complicated series of consecutive reactions, which need not even obey the law of mass action), but also to the cases of biological interest referred to above.

In general the state of a material system may be defined by indicating the values of a number of suitably chosen variables X_1, X_2, $\cdots$, and changes in the state of the system then naturally find expression in terms of the changes in the values of these variables.

In particular, certain of the variables in terms of which the state of the system is defined may be masses M_1, M_2, $\cdots$, the system being composed of a number of separate portions A_1, A_2, $\cdots$, which differ from one another in their properties in a discontinuous manner.

[1] C. R., 152, p. 1657, 1911.

[2] Abstract of a paper presented at the New York meeting of the Physical Society, March 2, 1912.

Any change in the system, which thus involves one or more of the variables M, is spoken of as a "change of state" in the narrower sense.

In particular we may consider those changes of state, in which only the variables M are allowed to change, the remaining variables being kept constant. The state of the system is then completely defined at every instant by the values of the variables M alone, and the course of the transformation going on in the system proceeds in accordance with a system of differential equations

$$\left.\begin{aligned} \frac{dM_1}{dt} &= F_1(M_1,\ M_2,\ \cdots\ M_i), \\ \frac{dM_2}{dt} &= F_2(M_1,\ M_2,\ \cdots\ M_i), \\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot & \\ \frac{dM_i}{dt} &= F_i(M_1,\ M_2,\ \cdots\ M_i). \end{aligned}\right\} \tag{1}$$

An obvious solution of this system of equations is

$$\left.\begin{aligned} M_1 &= C_1 = \text{constant}, \\ M_2 &= C_2 = \text{constant}, \\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot & \\ M_i &= C_i = \text{constant}, \end{aligned}\right\} \tag{2}$$

where the values of the i constants $C_1,\ C_2,\ \cdots$ are given by the i equations

$$\left.\begin{aligned} F_1(C_1,\ C_2,\ \cdots\ C_i) &= F_2(C_1,\ C_2,\ \cdots\ C_i) \\ &= \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot \\ &= F_i(C_1,\ C_2,\ \cdots\ C_i) = 0. \end{aligned}\right\} \tag{3}$$

Let us introduce into (1) the new variables

$$\left.\begin{aligned} u &= M_1 - C_1, \\ v &= M_2 - C_2, \\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot & \\ z &= M_i - C_i. \end{aligned}\right\} \tag{4}$$

We thus obtain

$$\left.\begin{aligned} \frac{du}{dt} &= f_1(u,\ v,\ \cdots z), \\ \frac{dv}{dt} &= f_2(u,\ v,\ \cdots z), \\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot\ \cdot & \\ \frac{dz}{dt} &= f_i(u,\ v,\ \cdots z). \end{aligned}\right\} \tag{5}$$

In the expansion of $f_1,\ f_2,\ \cdots$ by Taylor's theorem the absolute term must

vanish, owing to (2), (3), (4). We have therefore

$$\left.\begin{aligned}
\frac{du}{dt} &= a_1u + b_1v + \cdots + i_1z \\
&\quad + a_1'u^2 + \cdots + i_1'z^2 \\
&\quad + a_1''uv + \cdots + j_1''yz + \cdots, \\
\frac{dv}{dt} &= a_2u + b_2v + \cdots, \\
&\cdots\cdots\cdots \\
\frac{dz}{dt} &= a_iu + b_iv + \cdots.
\end{aligned}\right\} \tag{6}$$

The general solution of the system of equations (6) is

$$\left.\begin{aligned}
u &= A_1e^{\alpha t} + B_1e^{\beta t} + \cdots + I_1e^{\iota t} \\
&\quad + A_1'e^{2\ t} + B_1'e^{2\beta t} + \cdots + I_1'e^{2\iota t} \\
&\quad + A_1''e^{(\alpha+\beta)t} + \cdots + J_1''e^{(\kappa+\iota)t} \\
&\quad + \text{etc.}, \\
v &= A_2e^{\alpha t} + B_2e^{\beta t} + \cdots, \\
&\cdots\cdots\cdots \\
z &= A_ie^{\alpha t} + B_ie^{\beta t} + \cdots.
\end{aligned}\right\} \tag{7}$$

The constants A_1, A_2, $\cdots$ α, β, $\cdots$ may be evaluated by substituting the solution in the right- and left-hand member of the original equations and equating the coefficients of homologous terms. The exponents α, β, $\cdots$ may also be determined as the i roots of an equation of the ith degree obtained by neglecting all terms of a degree higher than the first in the original equations, and solving in the regular way.

If we restrict ourselves to two independent variables u and v, the exponents α and β take the form

$$\left.\begin{aligned}
\alpha &= \tfrac{1}{2}\{(a_1 + b_2) + \sqrt{(a_1 - b_2)^2 + 4a_2b_1}\}, \\
\beta &= \tfrac{1}{2}\{(a_1 + b_2) - \sqrt{(a_1 - b_2)^2 + 4a_2b_1}\}.
\end{aligned}\right\} \tag{8}$$

The solution becomes oscillatory as soon as

$$(a_1 - b_2)^2 + 4a_2b_1 < 0. \tag{9}$$

It is then convenient to write the solution in trigonometrical form, as follows

$$\left.\begin{aligned}
u &= e^{mt}(P_1 \cos nt + Q_1 \sin nt) \\
&\quad + e^{2mt}(P_2 \cos 2nt + Q_2 \sin 2nt + R_2) \\
&\quad + e^{3mt}(P_3 \cos 3nt + Q_3 \sin 3nt + R_3 \cos nt + S_3 \sin nt) + \cdots, \\
v &= e^{mt}(P_1' \cos nt + Q_1' \sin nt) + \cdots,
\end{aligned}\right\} \tag{10}$$

where

$$\left.\begin{aligned} m &= \tfrac{1}{2}(a_1 + b_2), \\ n &= \tfrac{1}{2}\sqrt{-\{(a_1 - b_2)^2 + 4a_2b_1\}}. \end{aligned}\right\} \qquad (11)$$

It is impossible in a short paper such as this to enter into much detail. By the way of a concrete illustration the following case may be briefly mentioned:

Consider a system which has had time to settle down to a steady state, so that the general conditions of the system and also the masses of the several species composing it are constant. Into this system let there be introduced a germ of some species A_i, which feeds on the waste products A_H of certain of the existing species A_h. Schematically the case may be represented by the symbols

$$A_h(\rightarrow A_H)\rightarrow A_i\rightarrow A_k\rightarrow.$$

It is required to investigate the mode of growth of A_i and the corresponding changes in the mass of A_H.

This case has been discussed by the author in a paper published in the Journal of the Washington Academy of Sciences.[1] It must suffice here to say that it leads to a system of equations of type (1), with two variables, and that therefore the growth of A_i takes on an oscillatory form as soon as a certain discriminant is negative. The significance, to a biological species, of such oscillatory growth, with its alternating periods of prosperity and depression, hardly needs to be pointed out.

THE THERMO E.M.F. OF THE NERNST FILAMENT.[2]

BY J. S. SHEARER.

ABOUT a year ago the writer observed a thermo current while working with a Nernst filament and was surprised at its magnitude as compared with those ordinarily observed. When hung by platinum wires in a bunsen flame so that one end was in the mantle and the other in the cone a fluctuating E.M.F. amounting to about one volt or even more was observed. It was not found possible to keep conditions steady enough to make any definite measurements when such a flame was used. As even the 220-volt filament is rather short it is necessary to have a high temperature gradient as well as to keep all parts of the filament at such a temperature that it will conduct if a potentiometer is to be used to measure the potential difference.

Platinum and platinum-rhodium wires were fused to the ends of the filament and passed through two-bore fireclay tubes. These were in turn slipped inside a thin-walled quartz tube for protection. The tube could be slid along in a platinum furnace with the windings bunched in the middle so that the temperature gradient was fairly steep. The E.M.F.'s of the two thermocouples and that of the filament against platinum were measured in succession by a potentiometer.

[1] Vol. 2, 1912, pp. 2, 49, 66.

[2] Abstract of a paper presented at the Washington meeting of the Physical Society, Dec. 27–30, 1911.

The results for one 220-volt filament are given below for the range of temperature available by this method. The middle of the furnace must be kept so hot as to nearly melt the platinum in order to get the temperature given. It is the intention of the writer to carry out measurements to higher temperatures and with other filaments with a carbon resistance furnace in the near future as well as to study some other features of such conductors.

$\Delta t°$	ΔE Volts.	$\frac{\Delta E}{\Delta t}$	$\frac{t_1° + t°}{2}$
20	.0080	.00040	1425° C.
50	.0210	42	1410
75	.0340	45	1397
125	.0530	42	1367
135	.0539	40	1347
210	.0820	39	1305
285	.1076	38	1038
290	.1110	38	1240
395	.1548	41	1157
435	.1738	40	867
440	.1860	41	980

It would thus appear that the thermo-electric power is more than forty times that of platinum platinum-rhodium for the same temperature interval

CORNELL UNIVERSITY.

THE EFFECT OF A MAGNETIC FIELD ON PHOTO-ELECTRIC EMISSION.[1]

BY ALBERT W. HULL.

THE following is a preliminary report of experiments which seem to have an important bearing on the mechanism of photo-electric emission and magnetization.

The facts are briefly as follows. Photo-electric emission from an aluminium plate in a high vacuum is reduced to a small fraction of its value by a magnetic field perpendicular to the plate. This effect increases with the strength of the field, but is greatly diminished by an electric field in such a direction as to drag the electrons from the plate. Thus, in the absence of an electric field, *i. e.*, when the illuminated plate and its surroundings are at the same potential, a magnetic field of 100 Gauss reduced the photoelectric emission to one twentieth of its value; with an electric field of 2 volts/cm. the same magnetic field reduces the emission to one half its value.

It is hard to see how a layer of adsorbed gas, electrified or otherwise, can account for this effect. For the number of collisions made by an electron in passing through the layer would be the same with or without the field. This is confirmed by the experiments made thus far, which show the effect of the mag-

[1] Abstract of a paper presented at the New York meeting of the Physical Society, March 2, 1912.

netic field to be independent of the nature of the gas or the thickness of the layer.

One is therefore forced to seek an explanation in a changed condition of the metal. According to the Maxwell-Langevin theory the molecules of a paramagnetic substance will orient themselves in a magnetic field so that their electric orbits are in planes perpendicular to the direction of the field, *i. e.*, parallel to the plate. If the photo-electric effect is due to a resonance which increases the amplitude of vibration beyond the point of stability, the direction of projection of the electrons will be parallel to the plate, and they will not escape unless aided by a strong electric field. This is in harmony with the experimental results obtained thus far, but it is surprising that a metal so slightly paramagnetic as aluminium should show such a large effect in comparatively weak fields.

Experiments with polarized light and diamagnetic substances are now in progress which may, it is hoped, throw some light upon these processes.

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THE THEORETICAL AND EXPERIMENTAL DETERMINATION OF REFLECTION COEFFICIENTS OF ABSORBING MEDIA.[1]

BY J. T. TATE.

THE object of this investigation was to compare the reflection coefficients of absorbing media calculated from the optical constants, obtained by the well-known reflection method of Drude, with the reflection coefficients photometrically observed on the *same* surface. Heretofore, on account of disturbing surface conditions, only casual agreement, of no value as an experimental verification of the reflection theory, had been found.

Comparisons were made in the visible spectrum for silver (light incident in both air and glass), gold, copper, steel, and fuchsin, the magnitudes of the reflection coefficients varying from .12 to .96. The reflection coefficients, photometrically measured, agree, in all cases, with those theoretically calculated from polarimetric observations on the same surface, thus showing the sufficiency of the present theory to account for these relations.

Owing to the fact that the photometric values vary more widely from the smooth curve than the theoretically calculated values, and since a consideration of the experimental errors involved in the measurements shows that this is to be expected, the reflection coefficients calculated from polarimetric measurements are distinctly more accurate than those observable by any direct photometric method.

[1] Abstract of a paper presented at the New York meeting of the Physical Society, March 2, 1912.